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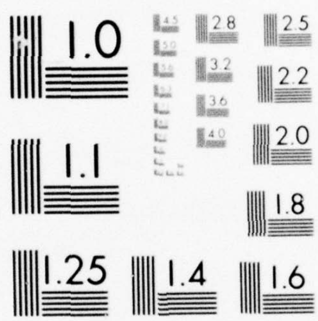

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by

(10) Charles Michael Johnson

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OPCODE1 is an excellent design tool for the conceptual design of a marine condenser. Optimized test cases run with OPCODE1 show that a condenser designed by the HEI method is nearly optimum with respect to volume.

Test cases with OPCODE2 show that enhancing the heat transfer on the shell-side by 80 percent yields a condenser with ten percent less volume than the unenhanced case.

Marine Steam Condenser Design Using Numerical Optimization

by

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Two separate computer codes were coupled with a constrained function minimization code to produce automated marine condenser design and optimization programs of vastly different complexity. The first program, OPCODE1, was developed from the Heat Exchange Institute's Standards for Steam Surface Condensers (HEI). The second program, OPCODE2, was developed from the sophisticated ORCON1, a computer code produced by the Oak Ridge National Laboratory. CONMIN, the optimization program, was developed at the Ames Research Center.

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NOMENCLATURE

English Letter Symbols

A_F - tube sheet area/number of tubes, ft^2/tube

A_H - heat transfer area, ft^2

A_i - internal tube area per linear foot, ft^2/ft

A_o - external tube area per linear foot, ft^2/ft

A_f - flow area for a single tube, ft^2

C - coefficient for calculation of overall heat transfer coefficient

D - tube outside diameter, ft

d - tube inside diameter, ft

E_i - internal heat transfer enhancement factor

E_o - external heat transfer enhancement factor

$F(\bar{X})$ - objective function

F_d - average tube flooding factor

F_n - tube flooding factor for the n-th tube

F_1 - fouling factor

F_2 - material correction factor

F_3 - temperature correction factor

f - tube-side friction factor

G - cooling water flow, gpm

$G_j(\bar{X})$ - inequality constraint

g - tube flow factor

g_L - acceleration due to gravity, ft/hr^2

g_o - acceleration due to gravity, ft/sec^2

$H_k(\bar{X})$ - equality constraint

h - enthalpy, BTU/lb

h_i - internal film heat transfer coefficient, BTU/(hr)(ft^2)(°F)

h_o - external film heat transfer coefficient, BTU/(hr)(ft^2)(°F)

h_o^* - external film heat transfer coefficient corrected for inundation, BTU/(hr)(ft^2)(°F)

h_{fg} - latent heat of condensation, BTU/lb

ICALC - control flag for COPES

k - tube constant, $k = s/g$

k_f - fluid conductivity, BTU/(hr)(ft)(°F)

k_w - wall conductivity, BTU/(hr)(ft)(°F)

k_v - vapor conductivity, BTU/(hr)(ft)(°F)

L - tube length, ft

LMTD - log mean temperature difference, °F

$\dot{m}$ - mass flow rate, lb/hr

N - number of tubes

NAC - number of active constraints

NCON - number of constraints

NDV - number of design variables

n^* - number of tubes in a vertical row above the n-th tube

P - absolute pressure, psia

PP - pumping power, ft·lbf/sec

ΔP_{ext} - tube exit loss, ft w.c.

ΔP_{ent} - tube entrance loss, ft w.c.

ΔP - sum of all tube-side pressure losses, ft w.c.

ΔP_t - internal tube friction loss, ft w.c.

Q	-	heat transferred, BTU/hr
q	-	iteration number
R_f	-	fouling resistance, (ft)(hr)(°F)/BTU
r_i	-	tube inside radius, ft
r_o	-	tube outside radius, ft
$\overline{S}$	-	search direction
s	-	outside area of tube per linear foot, ft^2/ft
T	-	temperature, °R
ΔT_{LM}	-	log mean temperature difference, °F
t_i	-	cooling water inlet temperature, °F
t_o	-	cooling water outlet temperature, °F
t_s	-	saturation temperature, °F
t_v	-	vapor temperature, °F
t_w	-	wall temperature, °F
U	-	uncorrected overall heat transfer coefficient, BTU/(hr)(ft^2)(°F)
U_c	-	corrected overall heat transfer coefficient, BTU/(hr)(ft^2)(°F)
U_i	-	overall heat transfer coefficient based on inside tube area, BTU/(hr)(ft^2)(°F)
V	-	cooling water velocity, ft/sec
VLB_i	-	lower side constraint on i-th design variable
VUB_i	-	upper side constraint on i-th design variable
W	-	steam flow, lb/hr
w.c.	-	water column
w	-	weight of cooling water, lb/gal
$\overline{X}$	-	vector of design variables

Dimensionless Groups

Pr - Prandtl number

Re - Reynolds number

Greek Letter Symbols

α^* - move parameter in optimization problem

β - ratio of A_F/A_f

β - parameter in method of feasible directions

ε - absolute roughness, ft

θ_j - push off factor in method of feasible directions

μ_f - fluid absolute viscosity, lb sec/ft^2

ρ_c - condensate density, lb/ft^3

ρ_{sw} - sea water density, lb/ft^3

ρ_v - vapor density, lb/ft^3

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I. INTRODUCTION

A. BACKGROUND

In the last ten years a revolution has swept the marine power plant industry that could result in the obsolescence of the marine steam power plant. The revolution was caused primarily by the use of the gas turbine as an alternative to marine, and more recently, to naval propulsion. Gas turbines brought about power plants which were more compact, lighter, but less fuel efficient than the steam power plants which they displaced.

When compared with the compact gas turbine, the massive size and weight of the marine steam power plant, which evolved in stride with the behemoth of the power industry, the stationary steam power plant, made this means of propulsion less desirable for naval vessels. Therefore, it has become imperative for the naval engineering community to develop a more efficient, more compact, lighter weight steam power plant.

As steam power plants are durable and they can burn a variety of fuels - both essential qualities when considering the Navy's combat readiness - they must not be allowed to be overdesigned out of existence. To make steam propulsion competitive with marine gas turbines, advanced concepts must be explored in all areas of steam propulsion. Such concepts as pressurized boilers, super critical cycles, enhanced

condenser tubes, and dropwise condensation must be developed further. Above all, overdesign by the use of unnecessary safety factors must be curtailed, and the minimum safe design must be developed and identified.

B. METHODOLOGY

In the United States the most prevalent criterion for the design and specification of surface condensers is based on the "square root of V" relationship as developed by the Heat Exchange Institute (HEI) [1]. Using this method, the overall heat transfer coefficient is calculated as a function of the square root of the cooling water velocity multiplied by correction factors for inlet cooling water temperature, tube wall thickness and material, and fouling.

The HEI method was adopted by the Department of the Navy, Bureau of Ships (now Naval Sea Systems Command) for the specification of U. S. Navy condensers by issuing Design Data Sheet 4601-1 (DDS) [2] in 1953. Henceforth this thesis will designate the preceding methodology as the HEI/DDS method.

With the advent of the high speed digital computer, numerical methods of solving complex engineering problems are now possible. A computer code has been developed to calculate the local heat transfer and thermodynamic properties of a large surface condenser on a row by row basis. Known as ORCON1, this code was developed by Oak Ridge National Laboratory (ORNL) under contract to the Office of Saline

Water during the period from 1968 to 1970 [3]. The program was based, in part, on the work performed by Eissenberg [4]. Eissenberg's experimental results led to correction factors on the basic Nusselt equation to account for inundation effects of tubes within a condenser tube bundle. Additionally, logic was developed to account for the pressure loss caused by the steam's passage through the tube bank with the accompanying reduction in saturation temperature; the heat resistance due to the presence of a noncondensable gas film; heat transfer enhancement factors on both sides of the tubes; and other important factors to yield a program which could calculate heat flux, overall heat transfer coefficient, noncondensable gas concentration, and fifteen additional parameters on a local, row by row basis.

Search [5] has used ORCON1 to perform parametric studies of an actual naval condenser. Tube enhancement, the high velocity flow allowed with titanium tubes, and dropwise condensation were investigated. The penalties paid in increased pumping power and increased cost were weighed against the gains realized with a more compact and with a lighter condenser.

In the open literature there is but one reference [6] to coupling a condenser analysis and design program with an optimization procedure that is capable of improving a given design.

The case for utilizing an optimizing design scheme for the condenser portion of a steam propulsion plant can easily be made by re-emphasizing the fact that in order for steam propulsion to remain a viable contender when the naval vessels of the late 1980's are designed, it must compete and succeed in an area that is rapidly being dominated by gas turbines. All components of the naval ship's steam propulsion plant will have to be critically designed to ensure that the minimum design will still perform as and when required.

C. OBJECTIVES

There were two primary objectives of this thesis.

The first objective was to develop a computer code based on the HEI/DDS method of condenser design, as this method is considered the industry standard. Coupling the HEI/DDS code with a numerical optimization program yields a complete design package. The design package can be used for trade-off studies, first cut analysis, and conceptual design.

The second objective was to couple ORCON1, with its capability of varying both internal and external tube enhancement factors, with a numerical optimization program to produce a more detailed design program.

These design tools provide the Naval architect and the Naval engineer with the means to optimize size, weight, design, and cost of the marine steam propulsion plant for ships of the 1980's; the enhanced design provides the optimum

streamlined design of a steam plant resulting in its reinstatement and continuance as a viable alternative to gas turbine propulsion.

II. NUMERICAL OPTIMIZATION

A. BACKGROUND

Nearly all design problems require either the minimization or maximization of a parameter or function. This parameter will be called the problem's objective function or design objective [7]. For the design to be acceptable, it must satisfy a set of design constraints. For example, if an engineer was designing a piping system to achieve the minimum in required pumping power, the minimum allowable flow delivered would be a meaningful constraint. Likewise a constraint that required the inside diameter of the pipe to be less than the outside diameter of the pipe would be a necessity.

If the problem could be formulated analytically with a great deal of simplicity, the minima or maxima could be found by using the methods of differential calculus or the calculus of variations. However, these methods would fail for all but the very simplest of problems.

A numerical method that would be satisfactory for relatively small scale problems would be an iterative solution technique. A simple computer program could be written containing a series of nested iteration loops that would vary the design parameters and solve the problem for a variety of values for each of the parameters. For small, easily formulated problems, the cost in central processor (CPU) time would not be excessive, and this method would be satisfactory.

However, for a serious engineering problem, this method quickly becomes too costly to pursue. For example, if the engineer had ten design parameters for which he wanted to try ten separate values, he would need to make ten billion calculations. If each calculation took ten CPU seconds, the solution would be available in approximately 3200 years! Thus a rational approach to design automation and optimization is obviously needed.

There are many optimization schemes available to the engineer. The various methods fall into three broad categories based on the type of problem to be solved: unconstrained minimization, solution of constrained problems by unconstrained minimization, and direct methods for solution of constrained problems [8]. An optimization program based on the last method was chosen for this research work.

B. CONSTRAINED FUNCTION MINIMIZATION (CONMIN)

Vanderplaats [9] developed an optimization program, CONMIN, capable of optimizing a very wide class of engineering problems. CONMIN is a FORTRAN program, in subprogram form, that optimizes a multi-variable function subject to a set of inequality constraints.

Three basic definitions are required [10]:

> Design Variables - Those parameters which the optimization program is permitted to change in order to improve the design. Design variables appear only on the right side of an equation, are continuous and have continuous first derivatives.

Design Constraints - Any parameter which must not exceed specified bounds for the design to be acceptable. Design constraints may be linear or non linear, implicit or explicit, but they must be functions of the design variables. Design constraints appear only on the left side of equations.

Objective Function - The parameter which is going to be minimized or maximized during the optimization process. The objective function may also be linear or non linear, implicit or explicit, and must be a function of the design variables. The objective function usually appears on the left side of an equation. The only exception is if the objective function is also a design variable.

As can readily be seen by the definitions above, design constraints and objective functions are usually interchangeable.

The number of design variables being utilized for an optimization is equivalent to the dimension of the design space in which the design is being calculated. Thus, if an optimization problem has four design variables specified, the design will be carried out in four-space.

Assuming that the optimization process requires the minimization of a particular objective function, the general optimization problem can be stated as:

Find the vector of design variables, $\overline{X}$, to minimize $F(\overline{X})$ subject to the constraints

$$G_j(\overline{X}) \leq 0.0 \ , \quad j = 1,NCON \qquad (1)$$

$$VLB_i \leq X \leq VUB_i \ , \quad i = 1,NDV \ . \qquad (2)$$

In the general problem statement, $F(\overline{X})$ is the objective function, there are NDV design variables, and NCON constraints. VLB_i and VUB_i are the lower bounds and upper bounds respectively on the i-th design variable. If the inequality

condition of equation (1) is violated, ($G_j(\overline{X}) > 0$), for any constraint, that constraint is said to be violated. If the equality condition is met, ($G_j(\overline{X}) = 0$), the constraint is active. If the inequality condition is met, ($G_j(\overline{X}) < 0$), the constraint is inactive. Because of the numerical problems involved in representing exact zero on a computer with a finite number of significant figures, the equality condition is represented by a band around the value $G_j(\overline{X}) = 0$. The band is equal to twice the constraint thickness (CT) and is shown in Figure 1. Figure 1 is a representation of a two-variable design space with the values of $G_j(\overline{X}) = 0$ plotted. In this instance,

$$\overline{X} = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \quad .$$

For n-space, $G_j(\overline{X})$ would appear as a hypersurface whereas for $n = 2$, the hypersurface degenerates to a single curve that can be easily represented.

Any design which satisfies the inequalities of equations (1) and (2) is referred to as a feasible design. If a design violates any of these constraints, it is an infeasible design. The minimum feasible design is said to be optimal. Note that if it is desired to maximize an objective function, the process reduces to minimizing the negative of the objective function.

CONMIN requires an initial vector of design variables, $\overline{X}$, which may or may not yield a feasible design. If the

initial design is infeasible, CONMIN moves towards a feasible solution with a minimal increase in the objective function [9]. The optimization process then proceeds in an iterative fashion with the following recursive relationship:

$$\overline{X}^{q+1} = \overline{X}^{q} + \alpha^{*}\overline{S}^{q}$$

where q is the iteration number and α^* is the move parameter, a scalar, which defines the distance of travel in the direction of search, $\overline{S}$.

The optimization process is divided into two parts. The first is the determination of $\overline{S}$ which will reduce the objective function without violating any constraints. The second is the determination of the scalar α^* so that $F(\overline{X})$ is minimized in this direction, a new constraint is encountered, or a currently active constraint is encountered again.

For the sake of discussion, consider a condenser design problem with two design variables, X_1 and X_2, where

$X_1 \equiv$ condenser tube outside diameter, and

$X_2 \equiv$ tube pitch to diameter ratio.

The objective function is condenser volume, $VOL(\overline{X})$. Assume that the tube bundle diameter must be greater than a specified value, BD_{min}, and that the cooling water pumping power must be less than a specified value, HP_{max}. Figure 2

is a graphical representation of the problem. Note the lines of constant objective function, with $VOL_1(\overline{X}) > VOL_2(\overline{X})$, and the initial design at point Ⓐ.

It must be reiterated that, while this example assumes a feasible initial design, this is not a requirement and CONMIN will also optimize when given an infeasible initial design.

The optimization begins by calculating the gradient of the objective function by using the finite difference technique. A perturbation of 0.01 is applied to each of the design variables in a single forward step. The gradient vector is therefore

$$\overline{\nabla}F(\overline{X}) \equiv \overline{\nabla}VOL = \begin{bmatrix} \dfrac{\partial(VOL)}{\partial X_1} \\ \\ \dfrac{\partial(VOL)}{\partial X_2} \end{bmatrix} \doteq \begin{bmatrix} \dfrac{\Delta VOL}{\Delta X_1} \\ \\ \dfrac{\Delta VOL}{\Delta X_2} \end{bmatrix} .$$

Because no constraints are active or violated, the greatest improvement in the objective function will be realized by moving in the direction of steepest descent so that

$$\overline{S} = -\overline{\nabla}VOL$$

as shown in Figure 3.

With the value of $\overline{S}$ now determined, it remains to find the move parameter, α^*, that will allow the greatest

improvement in the objective function. A one-dimensional search is carried out in the $\overline{S}$ direction until the value for α^* is found. This is point B on Figure 3. The location of point B terminates the first design iteration.

The second design iteration is begun by, once again, perturbing $\overline{X}$ to find $\overline{\nabla}$VOL. Instead of moving in the direction of steepest descent, however, a new $\overline{S}$ is found by the method of conjugate directions, developed by Fletcher and Reeves [11]. With this method, $\overline{S}$ is calculated by the following relationship:

$$\overline{S}^q = -\overline{\nabla} F(\overline{X})^q + \frac{\left|\overline{\nabla} F(\overline{X})^q\right|^2}{\left|\overline{\nabla} F(\overline{X})^{q-1}\right|^2} \overline{S}^{q-1} .$$

This is shown in Figure 4.

The advantage of using the Fletcher-Reeves method instead of the steepest descent is that convergence to an optimum is much faster. With the new search direction, $\overline{S}$, a search is performed in this direction until a constraint is encountered. This occurs at point C on Figure 4 at the pumping power constraint, thus terminating the second design iteration.

The third design iteration begins with the HP_{max} constraint active at point C on Figure 5. As $\overline{\nabla}$VOL is found, the gradient of the active constraint is found using the information from the same forward finite difference step.

Not only is a new $\overline{S}$ required that will reduce the objective function, but this new $\overline{S}$ must not violate the

active constraint. This problem may be solved by the method of feasible directions developed by Zoutendijk [12] and implemented by Vanderplaats and Moses [13].

The finding of a new $\overline{S}$ has now become a sub-problem which is a linear programming problem with a single quadratic constraint. This sub-problem [14] is stated as:

Find a vector $\overline{S}$ to maximize β subject to the constraints

$$\nabla F(\overline{X}) \cdot \overline{S} + \beta \leq 0 \tag{3}$$

$$\nabla G_j(\overline{X}) \cdot \overline{S} + \theta_j \beta \leq 0 \qquad j = 1,NAC \tag{4}$$

$$\overline{S} \cdot \overline{S} \leq 1 \tag{5}$$

where, for the case at hand, $\overline{\nabla} F(X) \equiv \overline{\nabla}\, VOL$, $\overline{\nabla} G_j(\overline{X}) = -\overline{\nabla} HP$, and $G_j(\overline{X}) = HP_{max} - HP$. NAC, the number of active constraints, is one in this instance.

If equation (3) is satisfied and β is positive, the resulting search direction will reduce the objective function and is defined as a usable direction. If equation (4) is satisfied and β is positive, $\overline{S}$ is a feasible direction because, for a small move in this direction, no constraints will be violated. θ_j is defined as the push-off factor for $G_j(\overline{X})$ and has the effect of pushing the design away from the active constraint. θ_j must be zero or positive to maintain a feasible design. For $\theta_j = 0$, $\overline{S}$ would be tangent to the active constraint. For $\theta_j >> 1.0$, $\overline{S}$ would be

pushed away from the active constraint and very nearly tangent to a line of constant objective function. For $\theta_j = 1.0$, the angle between constant objective function and the active constraint would be approximately bisected. If the maximum value of β obtainable from equations (3), (4) and (5) is zero, then no direction exists which will both reduce the objective function and satisfy the constraint, and the current design is optimal or is at least a local minimum. In this example, a usable and feasible direction exists and a one dimensional search leads to point D in Figure 5 where the minimum bundle diameter, BD_{min}, constraint is encountered. This ends the third iteration in the optimization process.

The fourth iteration begins as before, with the calculation of the gradient of the objective function and the active constraint. The sub-problem of equations (3) through (5) is again solved for a new $\overline{S}$.

It should be noted that the minimum bundle diameter constraint is assumed to be linear; therefore in equation (4) the push-off factor, θ_j, is set to zero allowing $\overline{S}$ to follow the constraint as shown in Figure 6. A one dimensional search is again carried out in the new $\overline{S}$ direction until a new constraint is encountered or an active constraint is re-encountered. Thus, the activated BD_{min} constraint is "ridden" until no further design improvement is realized. This occurs at point E on Figure 6 and the fourth design iteration is terminated.

For the fifth iteration, the same procedure is followed and the solution to the sub-problem characterized by equations (3) through (5) yields a value of zero for β. Thus, there is no direction that will both reduce the objective function and satisfy the constraint and the current design at point E in Figure 7 is optimal.

Figure 8 illustrates the value of using optimization techniques to solve the design problem. Assume an initial design at point A such that the minimum tube outside diameter is active. A reduction in the tube pitch to diameter ratio will yield a design improvement until the minimum bundle diameter constraint is encountered at point B. At this point, neither the pitch to diameter ratio nor the outside tube diameter can be reduced independently as required to reduce the objective function, without violating the active constraints. Only by changing the two design variables in a particular manner can the minimum value of the objective function at point C be achieved.

This discussion of the methodology involved with CONMIN would not be complete without citing the program's limitations. The number of design variables (NDV) directly affects the computational time required to reach an optimum. Since the calculation of the gradient information required for each design variable at the beginning of each design iteration is found by using a single forward finite difference step, requiring a complete pass through the analysis portion of the program, there is a subsequent increase in CPU time

as NDV increases. Also, problems with many design variables tend to converge more slowly due to the interaction between the design variables and because of the numerical inaccuracy (machine related) generated during the optimization process. The number of design variables should therefore be kept small in order to expedite the optimization process. Vanderplaats [7] recommends a practical limit of twenty design variables.

The number of design constraints used is not limited in the same manner. Recall that the only time gradient information is stored for a constraint is when that constraint is active. Therefore, the sheer number of constraints will not adversely affect the optimization.

As can be seen in Figure 9, it is quite possible that the optimal design found is actually a relative optimum and not a global optimum. This problem can be overcome by starting the design with several different initial vectors, $\overline{X}$, until the same optimal design is repeated.

Equality constraints of the type

$$H_k(\overline{X}) = 0$$

are very difficult to provide for in the general optimization scheme [7]. By defining an objective function in which a weighting factor multiplies the parameter to be held constant, Y, and this product is summed with the parameter to be optimized, X,

$$\text{objective function} = X + \text{weighting factor} \times Y$$

the parameter to be held constant can be forced to the appropriate bound. The weighting factor is generally one that will keep both terms in the same order of magnitude but trial and error is sometimes required. Parameters can be held "constant" within ±0.5 percent.

C. CONTROL PROGRAM FOR ENGINEERING SYNTHESIS (COPES)

Recall that the optimization program, CONMIN, was written in subroutine form. Vanderplaats [15] has developed a main program to simplify the use of CONMIN and to further aid in the design optimization process.

The user must supply an analysis subroutine with the name ANALIZ. ANALIZ, in keeping with general good programming practice, must have three segments: input, analysis and output. Based on the value of a flag from COPES (ICALC = 1,2 or 3), ANALIZ performs the proper function. Finally, CONMIN and ANALIZ do not communicate directly with each other as COPES is the main program.

COPES is constantly being revised by Vanderplaats to better meet the needs of the engineer.

The COPES program currently provides four specific capabilities:

1. Single analysis - just as if COPES/CONMIN were not used.
2. Optimization - minimization or maximization of a multivariable function with limits imposed on other functions.

3. Sensitivity analysis - used to investigate the effect of changing one or more design variables on one or more calculated functions.
4. Two-variable function space - provides analyses of all specified combinations of two design variables.

This work is concerned only with the application of COPES/CONMIN to the optimized design of a marine condenser, therefore, items 3 and 4 are included only for completeness.

If there is no relative or absolute change in the value of the objective function for three design iterations, the optimum is found and COPES prints the appropriate message and terminates the program. If no feasible design can be found after ten design iterations, COPES prints the appropriate message and terminates the program.

Experience has shown that most design problems can be optimized within 20 design iterations and the maximum number of design iterations permitted is defaulted to this value. Thus, if the optimum value has not occurred in 20 design iterations, COPES will print the appropriate message and terminate the procedure.

COPES has simplified the procedures involved in using a sophisticated program such as CONMIN. Thus the engineer is freed from the unwanted role of systems analyst and may devote his talents to engineering.

III. OPTIMIZED CONDENSER DESIGN, VERSION 1 (OPCODE1)

A. DEVELOPMENT

The Bureau of Ships adopted the Heat Exchange Institute's Standards for Steam Surface Condensers [1] by issuing Design Data Sheet DDS 4601-1 [2] in October, 1953. The DDS is still being used to specify naval condensers.

The technique involved is based on calculating a value of the overall heat transfer coefficient, U_c, based on the cooling water velocity through the condenser tubes, the condenser tube wall thickness and material, the tube fouling factor, and the cooling water inlet (injection) temperature. Knowledge of these parameters and their associated correction factors leads to the simple formulation of U_c

$$U_c = F_1 F_2 F_3 \, C \, \sqrt{V} \quad .$$

The correction factors F_1, F_2, and F_3 are tabulated in references [1] and [2]. Reference [2] specifies a value of C = 270 for 0.625 and 0.750 inch outside diameter (o.d.), 18 Birmingham Wire Gauge (BWG) tubes. A value of C = 263 is used for 0.875 and 1.00 inch o.d., 18 BWG tubes.

Because of the simplicity of the HEI/DDS method of condenser design, and since the DDS is still the specifying document for naval condensers, the author chose to implement the HEI/DDS method for automated design. The combination of

COPES/CONMIN with the HEI/DDS method was named OPCODE1 (OPtimized COndenser DEsign, Version 1). The development of OPCODE1 is presented in Appendices A and B.

To add greater versatility to the HEI/DDS method, algorithms were developed for OPCODE1 to calculate a circular bundle geometry and the cooling water pumping requirement. The circular bundle geometry was designed from the long axis out. A central 12 inch diameter void to serve as the collection header for noncondensable gasses was provided along the bundle's longitudinal axis. Once the number of tubes was calculated, the tubes were placed in rows concentric to the central void and spaced with a 60 degree triangular pattern. To simplify the algorithm, and to provide continuous functions to COPES/CONMIN, partial tubes were permitted in a row and the outermost row was allowed to be partially filled.

The calculation of the mass flow rate of cooling water required began the calculation of the sea water (S-W) pressure drop and pumping power requirement.

The S-W pressure drop was divided into a component based on the sudden expansion and contraction losses caused by the flow entering and exiting the waterboxes; a component based on the sudden contraction and expansion losses caused by flow from the inlet waterbox into the inlet tube sheet and from the outlet tube sheet into the outlet waterbox; and a component based on the normal frictional losses associated with internal tube flow.

Reference 1 presents, in graphical form, the pressure drops for all the components. The graphical data from Figure SF-9 of reference 1 for the calculation of waterbox losses was implemented using a systems library interpolating subroutine. The S-W velocity in the waterboxes was taken as 75 percent of the velocity in the condenser tubes as specified in reference 16.

To simplify the tube-side pressure loss algorithm, the friction factor, f, was first calculated by solving the transcendental Colebrook equation [17]. Details of the solution are provided in Appendix B. An absolute roughness of 5×10^{-6} feet was assumed as representative of drawn tubing. With the value of f calculated, the tube-side pressure drop, ΔP_t, was calculated using the familiar Darcy-Weisbach formula [17]:

$$\Delta P_t = f \left(\frac{L}{d}\right)\left(\frac{V^2}{2g_o}\right) .$$

The tube sheet entrance and exit losses were calculated by utilizing the area ratio technique developed in reference 18. With this method, the flow area associated with each tube was calculated

$$A_F = \frac{\text{tube sheet area}}{\text{number of tubes}}$$

followed by the calculation of the internal flow area for an individual tube, A_f and the ratio of the two areas:

$$\beta = \frac{A_f}{A_F} \ .$$

With the value of β calculated, the entrance loss was calculated with the relation

$$\Delta P_{ent} = 0.5(1.0 - \beta^2)\left(\frac{V^2}{2g_o}\right) \qquad \text{[feet of water column]}$$

and the exit loss was calculated with the relation

$$\Delta P_{ext} = (1.0 - \beta^2)^2\left(\frac{V^2}{2g_o}\right) \qquad \text{[feet of water column].}$$

Although the heat transfer calculations performed in OPCODE1 were for a single pass condenser, expansion of the program to multiple pass condensers is feasible. To simplify this future expansion, the waterbox pressure loss was multiplied by the number of tube passes, read as an input variable.

The pumping power was now easily calculated

$$PP = N \cdot V \cdot A_f \cdot \rho_{sw} \cdot P \qquad \left[\frac{ft \cdot lbf}{sec}\right] \ .$$

The input variables required for the use of OPCODE1 are listed in the User's Manual provided as Appendix C.

B. OPCODE1 VERIFICATION

It was desirable to verify the performance of OPCODE1 as a predictor of condenser performance by comparison with

actual experimental data. Complete and accurate data was not available, therefore, another method of model verification was sought.

Using the design data from the condenser technical manuals for two classes of ships, the CVA 67 and the DE 1040, an attempt was made to repeat the design of the condensers. The two condensers are vastly different in size; the CVA 67 has a heat transfer area of 16,011 square feet while the DE 1040 class condenser has a heat transfer area of 6600 square feet.

The results of the design of the CVA 67 by OPCODE1 are tabulated in Table I with the data from the condenser technical manual [19] included for comparison. Very close agreement was achieved for all parameters except tube-side pressure drop. This difference was attributed to the tube sheet layout by OPCODE1 and the fact that no steam lanes were accounted for. The addition of steam lanes would tend to increase the tube-side pressure drop since more tube sheet area would be unused as tube sites. Thus the entrance and exit losses associated with the tube sheets would be greater than predicted by OPCODE1.

The results of the design of the DE 1040 class condenser by OPCODE1 are tabulated in Table II with the data from the condenser technical manual [20] included for comparison. Excellent correlation was achieved with all parameters within three percent of the specifications except for bundle diameter and tube-side pressure drop. Since no provision was

made for the calculation of circumferential steam lanes in OPCODE1, the bundle diameter calculated was less than the prototype.

Since the DE 1040 condenser has a basically circular bundle geometry, close agreement was expected between the calculated tube-side pressure drop and the value specified in the technical manual. This was not the case. One plausible explanation could be that the designers specified a large factor of safety for this parameter.

These results confirm that the designers of the CVA 67 and the DE 1040 main condensers did, in fact, use the HEI/DDS method for the calculation of the heat transfer parameters and, with the notable exceptions of tube-side pressure drop and bundle diameter, OPCODE1 accurately predicts these parameters at the full power design point.

If the limitations imposed on tube-side pressure drop and bundle diameter by the exclusion of steam lanes from OPCODE1 are acknowledged, the results received from OPCODE1 can be viewed as a "first cut" analysis. This was the original purpose of developing this program.

C. LIMITATIONS OF OPCODE1

OPCODE1 is insensitive to shell-side conditions. The saturation steam pressure and the saturation steam temperature are assumed to remain constant as the steam passes through the bundle, whereas the steam flow actually experiences a pressure drop with a resulting decrease in saturation

temperature as the steam passes through each row of tubes. As a result, OPCODE1 makes no attempt to specify steam lanes, either circumferential or radial, since the proper design of steam lanes is a strong function of local steam pressure.

OPCODE1 has no provision for the application of tube enhancement factors due to the simple manner in which the corrected overall heat transfer coefficient is computed. The usual method for the calculation of U_i [21] is:

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{A_i \ln (r_o/r_i)}{2\pi k_w L} + R_f + \frac{A_i}{A_o}\frac{1}{h_o}} \tag{6}$$

where the internal film heat transfer coefficient is given by the Colburn form of the convective film heat transfer correlation [21]:

$$h_i = 0.023 \, (Re)^{0.8} (Pr)^{1/3} \left(\frac{k_f}{d}\right) \tag{7}$$

The outside film heat transfer coefficient is given by Nusselt's equation [21] corrected for the inundation, or condensate rain, effects of upper tubes on lower tubes in the bundle by including the factor n* in the denominator, where n* is the number of tubes in a vertical row above the i-th tube

$$h_o = 0.725 \left[\frac{\rho_c(\rho_c - \rho_v) g_L h_{fg} k_c^3}{\mu\, n^* D\, (t_v - t_w)}\right]^{1/4} \tag{8}$$

With h_i and h_o in the forms given by equations (7) and (8), enhancement factors can be applied as multipliers of these equations and equation (6) will yield a value for the enhanced overall heat transfer coefficient, U_i^*.

None of the foregoing is possible with the HEI/DDS based OPCODE1.

Finally, since OPCODE1 is insensitive to steam conditions, the effect of noncondensable gasses on the heat transfer characteristics of the condenser are unknown.

IV. OPTIMIZED CONDENSER DESIGN, VERSION 2 (OPCODE2)

A. BACKGROUND

In the late 1960's, engineers at the Oak Ridge National Laboratory developed a sophisticated computer code under contract to the Office of Saline Water. This code, called ORCON1 [3], was generated to aid in the analysis and parametric study of large, generally circular steam condensers for use in large scale, multistage distillation plants for the production of potable water from sea water by the flash evaporation process.

Much of ORCON1 was dependent on Eissenberg's research work [4] on the effects of condensate rain on the shell-side convective heat transfer coefficient.

The program analyzes a single pass, circular or semi-circular condenser, with steam flowing on the shell-side of the tubes and variable salinity water flowing on the tube-side. An optional, rectangular air cooler bundle is provided for, as well as elementary, shell-side baffles. The bundle is divided into 30 degree sectors and symmetry about the central axis may be employed to reduce computational effort. The tubes are placed on a 60 degree equilateral triangular pattern of concentric rows with the rows added from the outermost row to an inner void provided along the bundle's longitudinal axis. This serves as a collection header for noncondensable gasses prior to passage through the air cooler, if specified. The steam is assumed

to flow radially from the outside of the bundle to the central void. Figure 10 shows the ORCON1 model of a steam condenser with optional baffles and cooler.

ORCON1 proceeds with sector by sector, row by row calculations of the following quantities:

a) Saturation temperature of the steam entering the row.

b) Pressure of the steam plus noncondensable gas entering the row.

c) Steam flow entering the row.

d) Steam and noncondensable gas velocity at the minimum cross section in the row.

e) The fraction of noncondensable gas by weight.

f) The overall heat transfer coefficient for the average tube in the row.

g) The steam-side condensing coefficient.

h) The tube-side heat transfer coefficient.

i) The shell-side film heat transfer coefficient composed of the noncondensable gas film plus the condensate film.

j) The shell-side Reynolds number based on the mass flow at the minimum cross sectional area in the row.

k) The heat flux per square foot of condenser tube.

l) The shell-side friction factor.

m) The mass flow rate of steam plus noncondensable gas at the minimum cross section in the row.

n) The cooling water temperature at the inlet end of the condenser tube.

o) The cooling water temperature at the outlet end of the condenser tube.

p) The heat transfer coefficient for the noncondensable gas film.

q) The number of tubes per row.

r) The cumulative shell-side pressure drop from row 1 to row n.

In addition to the above parameters, the area weighted overall heat transfer coefficients for the condenser section, the cooler section, and the combined condenser are used to calculate the "back calculated" log mean temperature difference (LMTD). This value of the LMTD, when compared with the LMTD calculated by standard means using the saturation steam temperature and the average cooling water inlet and exit temperatures, represents the loss in average thermal driving force due to pressure drops within the bundle.

The tube internal film heat transfer coefficient is calculated by the Colburn equation multiplied by the internal enhancement factor

$$h_i = 0.023\,(Re)^{0.8}\,(Pr)^{1/3}\,(\frac{k_f}{d})(E_i) \quad .$$

The uncorrected external film heat transfer coefficient is calculated using the basic Nusselt equation [21]:

$$h_o = 0.725 \left[\frac{k_c{}^3\ \rho_c{}^2\ h_{fg}\ g_L}{\mu\ D\ (t_v - t_w)}\right]^{1/4} (E_o) \ . \qquad (9)$$

The value of h_o calculated in equation (9) is for a single tube. Eissenberg [4] corrects for inundation effects

by first calculating a tube flooding factor using the following relation:

$$F_n = 0.6F_d + (1 - 0.5647F_d)n^{-0.20} \quad .$$

F_d is an input parameter and is a function of both tube spacing to diameter ratio and tube orientation [3,22]. The condensate film coefficient for the typical tube in the n-th row is then calculated by correcting the value of h_o from equation (9):

$$h_o^*(n) = [nF_n - (n-1)F_{n-1}]h_o$$

To model the main condenser of the CVA 67, one quarter of the full circular bundle was specified. With two bundle quarters placed back to back as shown in Figure 11, the steam lanes and tube arrangement closely approximated the CVA 67 tube sheet as shown in Figure 12 from reference 19.

The combination of the COPES/CONMIN optimization package with a suitably modified ORCON1 produced OPCODE2 (OPtimized COndenser DEsign, Version 2).

B. MODIFICATIONS TO ORCON1

The original ORCON1 had neither tube-side pressure drop calculations nor volumetric calculations. The subroutines developed for OPCODE1 to calculate the tube-side pressure drop and pumping power were installed in ORCON1 when

converting it to OPCODE2. An equation for the calculation of condenser volume based strictly on the model as developed for the CVA 67 main condenser and shown in Figure 10 was added to ORCON1.

The flowchart given in Figure 13 illustrates the original program logic for ORCON1. Once all calculations were completed, a test for the exit steam fraction was made against an input target value. If the target value was not met, and depending on the value of an input flag, either the length of the condenser tubes or the quantity of inlet steam was varied, and the calculations were repeated until the target value and the calculated values agreed. The adjustment of tube length or inlet steam was performed in subroutine ADJUST.

It was felt that the quantity of inlet steam was generally the value which should drive the entire design of the condenser and should therefore remain a constant. Similarly, the tube length was a good candidate for inclusion in the optimization program as a design variable. For these reasons, subroutine ADJUST was removed from ORCON1.

The original ORCON1 provided logic for multiple data runs. This capability was removed since COPES/CONMIN requires a "once through" analysis program. Figure 14 shows the sections of ORCON1 removed during the conversion to OPCODE2.

Search [5] had previously modified ORCON1 so as to calculate the shell-side heat transfer coefficient either

with the original equation from the work of Eissenberg [4] or by using the relation specified by the manufacturer of Korodense condenser tubes [23]. This facility was left in OPCODE2.

ORCON1 was not originally a machine independent program as it had been tailored for operation on IBM (International Business Machines) equipment. This was not a desirable characteristic and programming changes were made to ensure that ORCON1 was machine independent and that OPCODE2 would remain machine independent.

ORCON1 uses iterative techniques to solve for quantities such as condensation rate, steam mass flow rate, and pressure drop balance between sectors. The description of subroutine ADJUST is an excellent example of such an application.

CONMIN uses perturbation techniques to calculate the gradient information required for each design variable and for each active design constraint during an optimization iteration.

Since ORCON1 has the capability to make design decisions, a perturbation by CONMIN would cause an adjustment by ORCON1. The two programs therefore worked at cross purposes.

It was not possible to remove all of these design decision points from ORCON1 because of the strong coupling between the subroutines. The decision was made to remove only ADJUST and to leave the other design decision points intact.

This problem affected the choice of parameters that could be used as design variables and the range of values that the chosen design variable was permitted to assume.

Another problem area developed because many of the thermodynamic properties were calculated in ORCON1 by subroutines that use logarithmic functions to approximate the thermodynamic curves. If the arguments for these functions take on values less than or equal to zero, the function is undefined. While constraints could be added as part of the optimization process, the computation would stop during the pass through the analysis.

Tests were put before all calculations that involved logarithmic evaluation and before all function evaluations where the denominator could take on values very close to zero. These tests, when activated, would make a "design decision" by setting the function to an approximate value such as:

$$\text{if} \quad x \leq 0.0001 \text{ , } \quad \text{then} \quad y = -10.0$$

$$\text{otherwise, } y = \ln x \text{ .}$$

These approximate values would cascade due to the large number of times the function was evaluated. Other mathematical instabilities also occurred.

The design variables or the values of the design variables that would trigger the original instability were found. The tests were removed and the troublesome design variables and/or the particular values that would cause the undesirable response were avoided.

C. OPCODE2 VERIFICATION

Verification of OPCODE2 as a predictor of condenser performance was attempted by inputing the design values from the CVA 67 technical manual [19] and comparing the condenser designed by OPCODE2 with the values given by the condenser technical manual [19]. Both the Eissenberg [3] and the Korodense [23] relations for tube inundation effects were used.

Because only one half of the condenser is designed by ORCON1, the quantity of inlet steam and the number of tubes specified by reference 19 were halved.

The program would not accept an inlet steam rate of greater than 200,000 pounds per hour (400,000 pounds per hour for the entire bundle).

Holman [21] states that up to a 20 percent increase in heat transfer rate may be realized by the ripples set up in the condensate film by steam passing over the film. The Korodense literature [23] indicates an enhancement due to the same phenomena as less than the 20 percent reported by Holman but also shows the enhancement to be a weak function of tube location in the bundle.

An enhancement, due to film ripples, of 14 percent was assumed for the current work.

The results of the verifications using both the Eissenberg and the Korodense relations are tabulated in Table III with the data from the CVA 67 technical manual [19] included for

comparison. Both relations yielded unsatisfactory design verification and in both cases a very conservative condenser was designed.

All parameters, as calculated by OPCODE2, were ten to twenty percent less than those from the actual condenser. With the removal of subroutine ADJUST, the condenser designed by OPCODE2 vented in excess of 20 percent of the inlet steam without condensing it.

It is believed that the effects of tube inundation give a shell-side film heat transfer coefficient which is too conservative as reflected in the reduced value of the overall heat transfer coefficient.

D. LIMITATIONS OF OPCODE2

Because ORCON1 has the capability to make design decisions and COPES/CONMIN requires a "once through" analysis, the coupling of these two programs in OPCODE2 created a situation where the programs were working against each other. This placed a limitation on which parameters could be used as design variables and on what range of values these design variables could use.

The condenser designed by OPCODE2 was very conservative, a condition caused primarily by the conservative value of the overall heat transfer coefficient calculated.

Accepting these limitations, it was felt that OPCODE2 should be further developed and that case studies should be performed.

V. RESULTS

A. EXPLANATION OF THE CASE STUDIES

The case studies were devised to best exercise the attributes of OPCODE1 and OPCODE2, and were made as realistic as possible so as to simulate the problem of a condenser design and specification during the early stages of power plant design. Only input parameters that would normally be available were used.

When comparing the results from the different cases, two cautions must be kept in mind. First, since all the cases involve four to six design variables, the design is taking place in a four to six dimensional design space and intuition on how an optimized design "should" turn out is not always applicable. Secondly, the percentage change referred to in each case is calculated based on the initial design for that particular case.

1. Constraint Framework for OPCODE1

In order to simulate an actual trade off study, the constraints for each case study were kept the same, even though an unimportant constraint could become active during a particular case study. In this way, each case study could be directly compared with all others.

The main condenser for the CVA 67 was to be designed with a maximum bundle diameter of ten feet; a terminal temperature difference (pinch point) of at least five degrees

Fahrenheit (°F) but not more than 35°F; a cooling water temperature rise of at least five °F, but not more than 20°F; and a ratio of tube sheet hole area to tube sheet area without the drilled holes of less than 0.36.

The constraint on bundle diameter was chosen only because it is a reasonable value. If more or less vertical space was available in a proposed machinery arrangement, the diameter constraint would be appropriately changed. The lower constraint on pinch point came from reference 1 which called for a minimum terminal temperature difference of five °F. No reference to an upper limit on pinch point could be found, but several technical manuals specified temperatures in the range of 20°F to 45°F. A value of 35°F was therefore chosen as the upper bound on the terminal difference.

Reference 24 states that the difference in temperature between the steam and cooling water streams entering the condenser, or temperature range, is ordinarily kept to 20°F, and that the cooling water temperature rise is usually made about five °F less than the temperature range. Since the CVA 67 exhausts steam with a saturation temperature of 125°F and reference 3 calls for a cooling water injection temperature of 75°F, the temperature range used was 50°F and the cooling water temperature rise upper limit was 45°F. As the guidance given by reference 24 seemed inappropriate and since neither reference 1 nor reference 2 specifies limits on cooling water temperature rise, the lower limit was

arbitrarily set at five °F and the upper limit was arbitrarily set at 20°F. The amount of tube sheet material that can be removed by drilling for the installation of tubes is specified at 24 percent of the blank tube sheet area by reference 2. Since OPCODE1 does not allow for steam lanes in the design of a condenser, and since these steam lanes would provide blank tube sheet area, the 24 percent limit was raised to 36 percent.

To ensure that an unrealistic tube wall thickness was not specified, a constraint on the wall thickness was added. The wall thickness was calculated from the current values of tube outside diameter and tube inside diameter, and the constraint applied. Values of wall thickness in the range from BWG 24 (0.022 inch) to BWG 12 (0.109 inch) were used as the lower and upper constraints.

In summary, the general design constraints and the associated upper and lower bounds were:

$$0.022 \leq \text{tube wall thickness (inch)} \leq 0.109$$

$$1.0 \leq \text{bundle diameter (feet)} \leq 10.0$$

$$5.0 \leq \text{terminal temperature difference (°F)} \leq 35.0$$

$$5.0 \leq \text{sea water temperature rise (°F)} \leq 20.0 \; .$$

These design constraints and the associated upper and lower bounds were used in all of the OPCODE1 test cases except where specifically modified.

2. Design Variable Framework for OPCODE1

The condenser tube outside and inside diameters were used as design variables. The side constraints were set to correspond with the values of normally available tubes [1]. The tube outside diameter was allowed to vary in the range between 0.625 inch and 1.25 inch. The tube inside diameter was allowed to vary from 0.407 inch to 1.206 inch.

The tube pitch is defined as the center to center spacing between tubes. The pitch to diameter ratio (S/D) is an accurate measure of how closely packed the tube bundle is. Generally accepted S/D ratios lie in the range of 1.3 to 1.7. However, to give greater latitude to this design variable, and since OPCODE1 was insensitive to shell-side conditions, the S/D ratio was allowed to vary within the range from 1.1 to 3.0.

There was no guidance available on the range of tube lengths that would be applicable to a condenser of this size using 0.625 inch tubes. Reference 1 gave a range of recommended tube lengths of eight to fourteen feet for 0.625 inch outside diameter tubes with an upper limit on heat transfer surface area of 1000 square feet. In the range of the expected heat transfer area of 12,000 to 18,000 square feet, the recommended tube outside diameters were from 0.75 inch to 0.875 inch with tube lengths ranging from 16 to 24 feet. Since the lower bound was not considered to be as crucial as the upper bound, it was set at one foot. The upper bound on tube length was set at 25 feet.

Cooling water velocity generally ranges from three to nine feet per second for all common tube materials except titanium which has an upper bound of 15 feet per second.

In summary, the general design variables and the associated side constraints were:

0.625 $\leq$ tube outside diameter (inch) $\leq$ 1.25

0.407 $\leq$ tube inside diameter (inch) $\leq$ 1.206

1.1 $\leq$ pitch/diameter ratio $\leq$ 3.0

1.0 $\leq$ tube length (feet) $\leq$ 25.0

3.0 $\leq$ cooling water velocity (feet/second) $\leq$ 9.0

These design variables and the associated side constraints were used in all of the OPCODE1 test cases except where specifically modified.

3. <u>Constraint Framework for OPCODE2</u>

The same constraints that were used for OPCODE1 were used for OPCODE2 with several additional constraints required due to the physical calculations performed.

To ensure that the cooler was not designed to be wider than the void inside diameter, the ratio of cooler width to void diameter had an upper bound of 1.0 and a lower bound of 0.1

As the initial design with OPCODE2 vented over 20 percent of the inlet steam without condensing it, an

upper bound on the exit steam fraction was set at five percent. The lower bound was set to zero.

Since OPCODE2 was attempting to allow for a central steam lane, the upper limit on bundle diameter was set at 12 feet and the lower limit was set at five feet.

Bundle volume had an upper limit of 1500 cubic feet and a lower limit of 100 cubic feet. These limits had been used satisfactorily with OPCODE1.

To ensure that the cooler height did not become larger than the band of condenser tubes from the outside diameter of the bundle to the inner void, the ratio of cooler height to tube band width was calculated. This ratio had an upper limit of 1.0 and a lower limit of 0.01.

The pinch point and the sea water temperature rise had the same range as was used for OPCODE1.

The tube wall thickness was not used as a design constraint in OPCODE2 as it had been in OPCODE1. Instead the tube inside diameter was used, with the lower constraint set at 0.407 inches and the upper constraint set at 1.206 inches to correspond with the values of normally available [1].

In summary, the general design constraints and the associated upper and lower bounds were:

$$0.1 \leq \text{cooler width/void diameter} \leq 1.0$$

$$0.0 \leq \text{exit steam percentage} \leq 5.0$$

$$5.0 \leq \text{bundle diameter (feet)} \leq 12.0$$

$100. \leq$ bundle volume (cubic feet) $\leq 1500.$

$0.01 \leq$ cooler height/tube band width ≤ 1.0

$0.407 \leq$ tube inside diameter (inch) ≤ 1.206

$5.0 \leq$ terminal temperature difference (°F) $\leq 35.$

$5.0 \leq$ sea water temperature rise (°F) $\leq 20.$

4. Design Variable Framework for OPCODE2

The condenser tube outside diameter and wall thickness were used as design variables. The side constraints were set to correspond with the values of normally specified tubes [1]. The tube outside diameter had a lower side constraint of 0.625 inch and an upper side constraint of 1.25 inch. The tube wall had a lower side constraint of 0.022 inch and an upper side constraint of 0.109 inch.

Tube length had the same side constraints as were used for OPCODE1.

The tube pitch to diameter ratio had a lower side constraint of 1.4 and an upper side constraint of 2.0. This band of allowable values was reduced from that used with OPCODE1 because of instabilities that developed for values of this variable outside of this band. More problems occurred at the lower end of the range than at the upper end. These problems originated from the tubes coming too close together and causing an excessively high steam velocity with a subsequent large pressure drop through a row of tubes. Since condenser pressure was already low,

passage through very few rows led to a negative steam pressure and thus the computational problems associated with the logarithmic calculation of thermodynamic properties discussed in Chapter IV.

The sea water velocity was allowed to vary within the range from three feet per second to ten feet per second. The upper side constraint was raised from the nine feet per second specified in OPCODE1 in an attempt to increase the mass flow rate of the cooling water and, therefore, the heat rejection rate.

In summary, the general design variables and the associated side constraints were:

$5.0 \leq$ tube length (feet) ≤ 25.0

$3.0 \leq$ sea water velocity (feet per second) ≤ 10.0

$0.625 \leq$ tube outside diameter (inch) ≤ 1.25

$0.022 \leq$ tube wall thickness (inch) ≤ 0.109

$1.4 \leq$ tube pitch/diameter ratio ≤ 2.0

B. CASE STUDIES USING OPCODE1

1. Case One

The objective of this test case was to minimize the pumping power requirement while holding the heat load to the condenser constant. The input parameters are presented in Table IV, the initial design is presented in Table V, and the results of the optimization are presented in Table VI.

These results show an 84 percent decrease in pumping power with a commensurate 37 percent increase in heat transfer surface area, a 55 percent increase in condenser volume, and a decrease of 27 percent in overall heat transfer coefficient. The log mean temperature difference remained constant.

The lower bound on tube wall thickness constraint and the upper bound on sea water temperature rise constraint were both active. No side constraints were active and no constraints were violated.

The decrease in pumping power is impressive but so are the increases in condenser dimensions with the implied increases in weight and cost.

2. Case Two

The objective of this test case was to minimize condenser volume with the heat load to the condenser held constant. The input parameters are presented in Table IV, the initial design is presented in Table V, and the results of the optimization are presented in Table VII.

These results show a 15 percent decrease in condenser volume with an unexpected 3.0 percent decrease in pumping power. This design can be understood by noting that the tube wall thickness was reduced from 0.049 inch to 0.022 inch causing an increase in material correction factor from 0.90 to 0.99. This increase was the primary factor in increasing the overall heat transfer coefficient 9.9 percent.

The lower constraint on tube wall thickness, and the upper constraint on tube sheet area ratio were both active. In addition, the lower side constraint on tube outside diameter and the upper side constraint on sea water velocity were both active. There were no violated constraints.

3. <u>Case Three</u>

The objective of this case was to maximize the heat rejected while holding pumping power constant. Since the pumping power is a calculated quantity, the method of combining pumping power and the heat rejected with an appropriate weighting factor in the objective function was used. The objective function was therefore:

$$OBJ = QREJ + A * POWER$$

and POWER was added as a design constraint with the target value of 68836 foot pounds per second as the upper constraint. With the weighting factor, A, set at 5600, the pumping power was constant within one percent. Turbine exhaust steam and auxiliary exhaust steam were both added as design variables to provide the driving force to increase the heat rejection rate.

The input parameters are presented in Table IV, the initial design is presented in Table V and the results of the optimization are presented in Table VIII.

These results show an 82 percent increase in the heat rejection rate with an accompanying 88 percent increase in surface area. The log mean temperature difference remained constant and the overall heat transfer coefficient decreased by 3.7 percent. The condenser volume increased by 78 percent and the number of tubes increased by 96 percent.

The upper constraint on pumping power was active, as desired, and the upper constraint on the tube sheet area ratio was active. There were no violated constraints and no active side constraints.

It should be noted that the turbine exhaust steam rate increased by 83 percent, whereas the auxiliary exhaust steam rate increased only 1.0 percent. Inspection of the component parts of QREJ explains the dominance by the main steam rate. The rejected heat was calculated by:

$$Q_{rej} = \dot{m}_{MS}\,\Delta h_{MS} + \dot{m}_{AS}\,\Delta h_{AS} + \text{heat from other sources}$$

where the subscript MS corresponds to main steam and the subscript AS corresponds to auxiliary steam. Heat from other sources was assumed constant during the optimization. The product $\dot{m}_{MS}\,\Delta h_{MS}$ was several orders of magnitude greater than the product $\dot{m}_{AS}\,\Delta h_{AS}$ and it therefore dominated the optimization process as a change in the $\dot{m}_{MS}$ design variable would yield a greater design improvement than would a like change in the $\dot{m}_{AS}$ design parameter.

In all probability, the $\dot{m}_{AS}$ design variable would not begin to make an appreciable move until the $\dot{m}_{MS}$ design variable approached its upper side constraint. This could not occur as the $\dot{m}_{MS}$ design variable had an unbounded upper side constraint.

No attempt was made to balance the flow of steam from the two sources to more evenly distribute the incoming heat load. Balancing could be accomplished by appropriately scaling the two mass flow rates so they would have approximately the same values.

4. Case Four

The objective of this case was to minimize the condenser volume while holding pumping power and the rejected heat constant. POWER was again included in the objective function

$$OBJ = VOL + A * POWER$$

and as a design constraint with a lower bound of 68836 foot pounds per second. The lower bound was the target value for pumping power. Trial and error solutions with various values of the weighting factor showed that a value of $A = 0.0$ gave a value of POWER which was constant within 0.5 percent. This was interpreted to mean that the optimization would have reduced the objective function further if the pumping power constraint was not present and that

the pumping power lower constraint was therefore always active. With the value of this constraint set at the target value for constant pumping power, inclusion of POWER in the objective function was unnecessary and A = 0.0 was appropriate.

The input parameters are presented in Table IV, the initial deisgn is presented in Table V and the results of the optimization are presented in Table IX.

These results show only a 2.0 percent decrease in condenser volume. The tube pitch to tube diameter ratio remained essentially constant as did the tube outside diameter. The tube wall thickness increased by 11 percent with an accompanying decrease in material correction factor from 0.90 to 0.88.

The lower constraint on pumping power was active, as discussed above. The upper constraint on sea water temperature rise, as well as the upper constraint on tube sheet area ratio were active. The upper constraint on sea water velocity was the only active side constraint. There were no violated constraints.

The results of this case study indicated that the circular bundle prototype was very close to having an optimum volume within the given design variable and design constraint framework.

Comparison of Cases Two and Four shows that a smaller condenser with essentially constant pumping power

was achieved with Case Two then with Case Four. This anomaly can be understood by comparing the constraints for the two cases.

Pumping power was not a constraint for Case Two and it was an active constraint for Case Four. Thus, the Case Four optimization had to contend with an additional constraint whereas, Case Two had more latitude within the design space and a better optimum was found.

5. Case Five

The objective of this case was to minimize the condenser overall length while holding pumping power and the heat rejected constant. Pumping power was included in the objective function:

$$OBJ = CLOA + A * POWER$$

and as a design constraint with a lower bound of 68836 foot pounds per second as the target value. With a weighting factor of 3.526×10^{-4}, pumping power was held constant within 0.5 percent.

The input parameters are presented in Tabe IV, the initial design is presented in Table V and the results of the optimization are presented in Table X.

The overall condenser length was reduced by 28 percent. The heat transfer area increased by 9.7 percent and the overall heat transfer coefficient decreased by 15 percent,

while the log mean temperature difference increased by 7.1 percent. The number of tubes increased 96 percent and the tube length decreased 44 percent. The tube wall thickness increased causing a decrease of 14 percent in the material correction factor thereby contributing to the decrease in overall heat transfer coefficient.

Accompanying the 23 percent decrease in condenser length was a compensating 37 percent increase in bundle diameter and an 18 percent increase in condenser volume.

The lower constraint on pumping power was active, as desired. The upper constraints on pinch point and on tube sheet area ratio were active. There were no active side constraints and no violated constraints.

6. Case Six

The objective of this case was to minimize pumping power while holding condenser volume and the heat rejected constant. For this case, volume was included in the objective function:

$$\text{OBJ} = \text{POWER} + \text{A} * \text{VOL}$$

and it was also included as a design constraint with an upper bound of 928.8 cubic feet as the target value. The usual trial and error procedure with various weighting functions was performed and the best results were obtained for a weighting factor of -2.5. With this value, condenser volume was held constant to within 1.3 percent.

The input parameters are presented in Table IV, the initial design is presented in Table V and the results of the optimization are presented in Table XI.

The pumping power was reduced by 35 percent. The log mean temperature difference and the heat transfer area remained essentially constant, while the tube wall thickness decreased 52 percent causing a ten percent increase in the tube material correction factor. The sea water velocity was reduced by 16 percent, however, and the overall heat transfer coefficient remained essentially constant. There were no active constraints, no violated constraints and no active side constraints.

Volume was not forced against its upper constraint as planned because the two members of the objective function were attempting to move in opposite directions. As power was decreased, the volume tended to increase. The negative weighting factor helped to turn this process around but the optimum was reached before the constraint was activated.

7. Case Seven

English has shown [25] that by placing boundary layer fences in front of the injection scoop of a ship, the pressure coefficient, and hence pumping power, will increase by 68 percent. These boundary layer fences cause shedding vortices to form behind them thus pumping water from the boundary layer around the ship into the condenser intake.

This case takes advantage of the increase in available pumping power by setting pumping power at a value 50 percent greater than the normal 68836 foot pounds per second, and holding this new value of pumping power constant while maximizing the rejected heat.

The constraints and design variables were set up exactly as they were for Case Three with the exception that the upper constraint on pumping power was raised to 103,250 foot pounds per second. POWER was included in the objective function as before and a weighting factor of 4095 yielded pumping power constant within 0.5 percent.

The input parameters are presented in Table IV, the initial design is presented in Table V and the results of the optimization are presented in Table XII.

The heat rejected was increased by 107 percent. The heat transfer area increased by 101 percent, and the log mean temperature difference remained constant. The tube wall thinned down by 53 percent causing an increase in the tube wall material correction factor of ten percent. The sea water velocity decreased 13 percent and the overall heat transfer coefficient increased 2.5 percent.

The upper constraints on pumping power and the tube sheet area ratio were active. There were no active side constraints and no violated constraints.

C. CASE STUDIES USING OPCODE2

1. Case Eight

This case was run assuming plain copper-nickel tubes with a 14 percent enhancement factor applied to the outside film heat transfer coefficient as described in Section IV(C) of this work. Steam baffles were specified and the inlet steam flow rate was set at 200,000 pounds per hour as only one half of a condenser bundle was being simulated. The Korodense equation from reference [23] was used to calculate the correction factor for tube inundation by condensate rain.

The objective of this case was to minimize condenser volume. The initial and optimum designs are presented in Table XVI.

The volume was reduced 13 percent and the heat transfer area increased 14 percent. The log mean temperature difference decreased 5.6 percent, the overall heat transfer coefficient increased 11 percent and the heat rejected increased 21 percent. The vented steam rate decreased 76 percent to five percent of the inlet steam flow rate. Finally, pumping power increased 65 percent and the sea water flow rate increased 35 percent.

The upper side constraint on sea water velocity as well as the lower side constraints on tube outside diameter, tube pitch to diameter ratio and tube wall thickness were all active. The upper constraint on vented steam rate was active. There were no violated constraints.

2. Case Nine

The objective of this case was to minimize the condenser volume when enhanced tubes were specified. The initial parameters were the same as those used in Case Nine with the exception of the outside enhancement factor which was set to 1.8. It was felt that this modest enhancement was attainable with the augmented tubes currently being manufactured.

The initial and optimum designs are presented in Table XVII.

Use of enhanced tubes reduced the condenser volume by 21 percent. The heat transfer area increased 2.6 percent, the overall heat transfer coefficient increased 34 percent, the log mean temperature coefficient decreased 11 percent and the heat rejected increased 21 percent. The vented steam rate decreased 76 percent to five percent of the inlet steam flow rate.

Pumping power increased 52 percent and the cooling water flow rate increased 35 percent. Tube length was increased by 2.7 percent and the tube inside diameter increased ten percent.

The pumping power calculated was based on smooth tubes. The most common augmented condenser tubes use either a rope design, a twist design, or internal flow promoters to enhance heat transfer. Reilly [26] has found that the pressure drop through enhanced tubes is 1.5 to 3.0 times the pressure drop through smooth tubes for the same flow conditions.

The upper side constraint on sea water velocity, as well as the lower side constraints on tube outside diameter, tube pitch to diameter ratio and tube wall thickness were all active. The upper constraint on vented steam rate was active, and there were no violated constraints.

3. <u>Case Ten</u>

This case was run using the same conditions as Case Eight with the exception that the original equation from ORCON1 was used to correct for tube inundation. Reference 3 specified a value for the flooding factor, FDAVE, of zero for pitch to diameter ratios greater than 1.4.

This value was used during this run of OPCODE2. The objective of this case was to minimize the condenser volume. The initial and optimum designs are presented in Table XVIII.

A more conservative design was produced with the Eissenberg equation than the design produced with the Korodense equation. The volume was reduced 5.3 percent and the heat transfer area increased 24 percent. The log mean temperature difference remained constant, the overall heat transfer coefficient increased by 8.9 percent, and the heat rejected increased by 33 percent. The vented steam rate decreased 83 percent to five percent of the inlet steam flow rate. Pumping power increased 75 percent and the sea water flow rate increased 35 percent.

The upper side constraint on sea water velocity, as well as the lower side constraints on tube outside

diameter, tube pitch to diameter ratio and tube wall thickness were all active. The upper constraint on vented steam rate was active. There were no violated constraints.

VI. CONCLUSIONS

The intent of this investigation was to couple a numerical optimization code with both a simple computer code for condenser design based on the HEI/DDS method and the more sophisticated ORCON1, and to test the programs developed with a variety of test cases to prove their viability. The results of these test cases were presented in Section V; the resulting conclusions are summarized here.

A. A condenser designed by the HEI/DDS method is very near the volumetric optimum in design, as only a 15 percent decrease in condenser volume was realized when volume was optimized using OPCODE1.

B. OPCODE1 is an excellent design tool for the conceptual design of a condenser to meet specified constraints such as length, height, and weight.

C. OPCODE1 can optimize a variety of objective functions, and with some trial and error application of weighting factors, equality constraints can be met.

D. OPCODE1 will yield an optimum design on which experience-based safety factors may be applied.

E. The ability to enhance tubes and the sensitivity of the program to shell-side conditions make the ORCON1-based OPCODE2 very attractive.

F. The basic equations and the research applied to the development of ORCON1 are sound, but a conservatively-designed condenser results. More baffles are required to more closely approximate an actual condenser and to aid in reducing the inundation effect on interior tubes.

G. The OPCODE2 designed condensers were more conservative than those designed by OPCODE1. This was caused by the detrimental effect on outside film coefficient by tube flooding. It is felt that this effect could be reduced by the addition of more baffles.

VII. RECOMMENDATIONS

In addition to the insight that this investigation has given into the generation of automated design programs for condenser design, it has also generated an awareness of this investigation's shortcomings. Presented herein are recommendations for improving upon and furthering development of the OPCODE family of condenser design programs.

A. OPCODE1 should be expanded to include the [illegible]ility for multi-pass condenser calculations, g[illegible]al options, material costing equations, strength of material considerations, and an algorithm to compute steam velocity through the rows of tubes to ensure that the velocity remains realistic.

B. Research should be performed to develop enhancement factor data for various tube types that can be applied to the basic equations used in OPCODE1.

C. ORCON1 should be rewritten with the intent of applying optimization techniques to the new program, and based on the equations and logic developed by Eissenberg, Korodense, and other investigators and manufactures, with the option to choose the desired relationship to be used.

D. In an effort to reduce the computer time required for a run using OPCODE2 (typically 35 CPU minutes), an investigation into using OPCODE1 as a pre-processor in front of a detailed analysis scheme is attractive.

E. Expand OPCODE2 to perform calculations for other than a circular bundle.

VIII. FIGURES

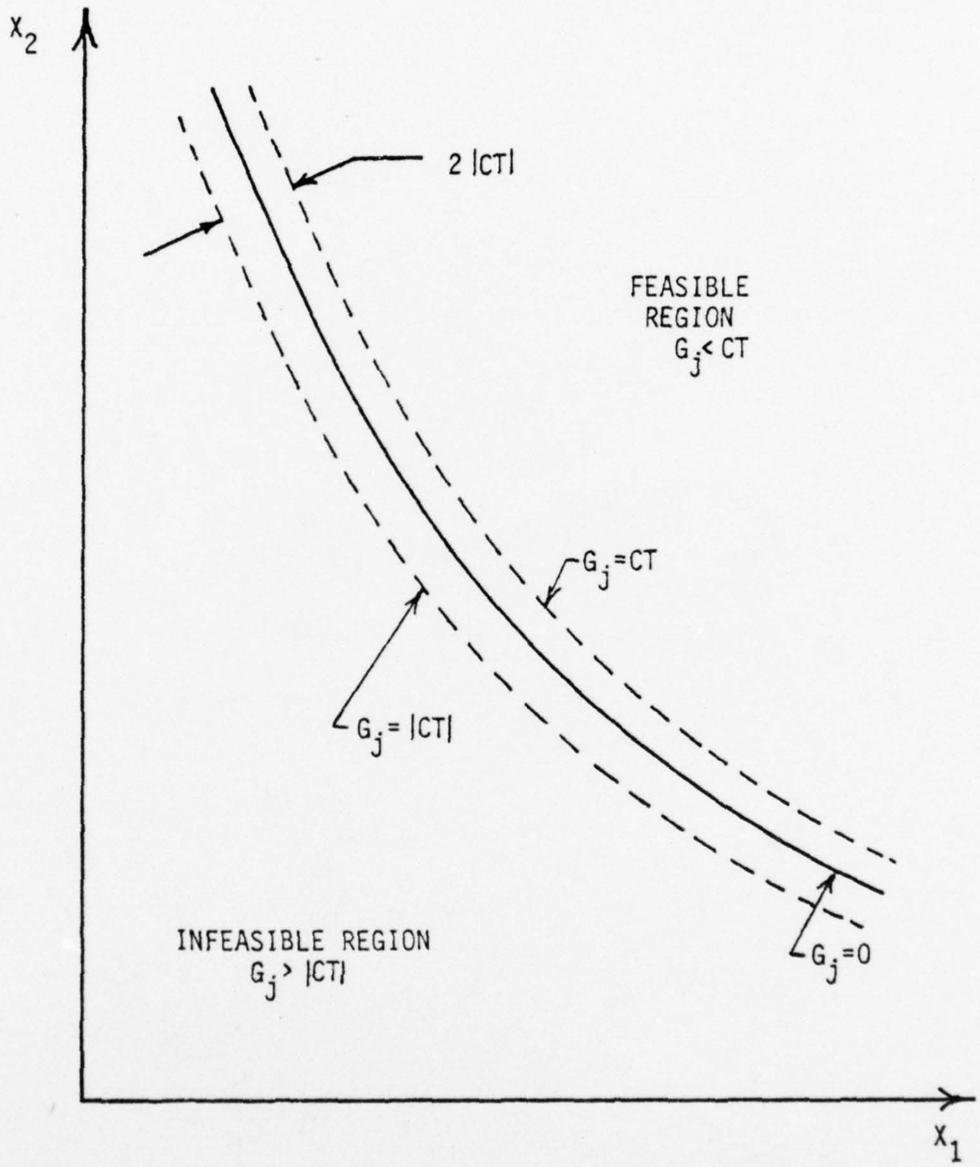

FIGURE 1. Significance of the Constraint Thickness (CT) Parameter

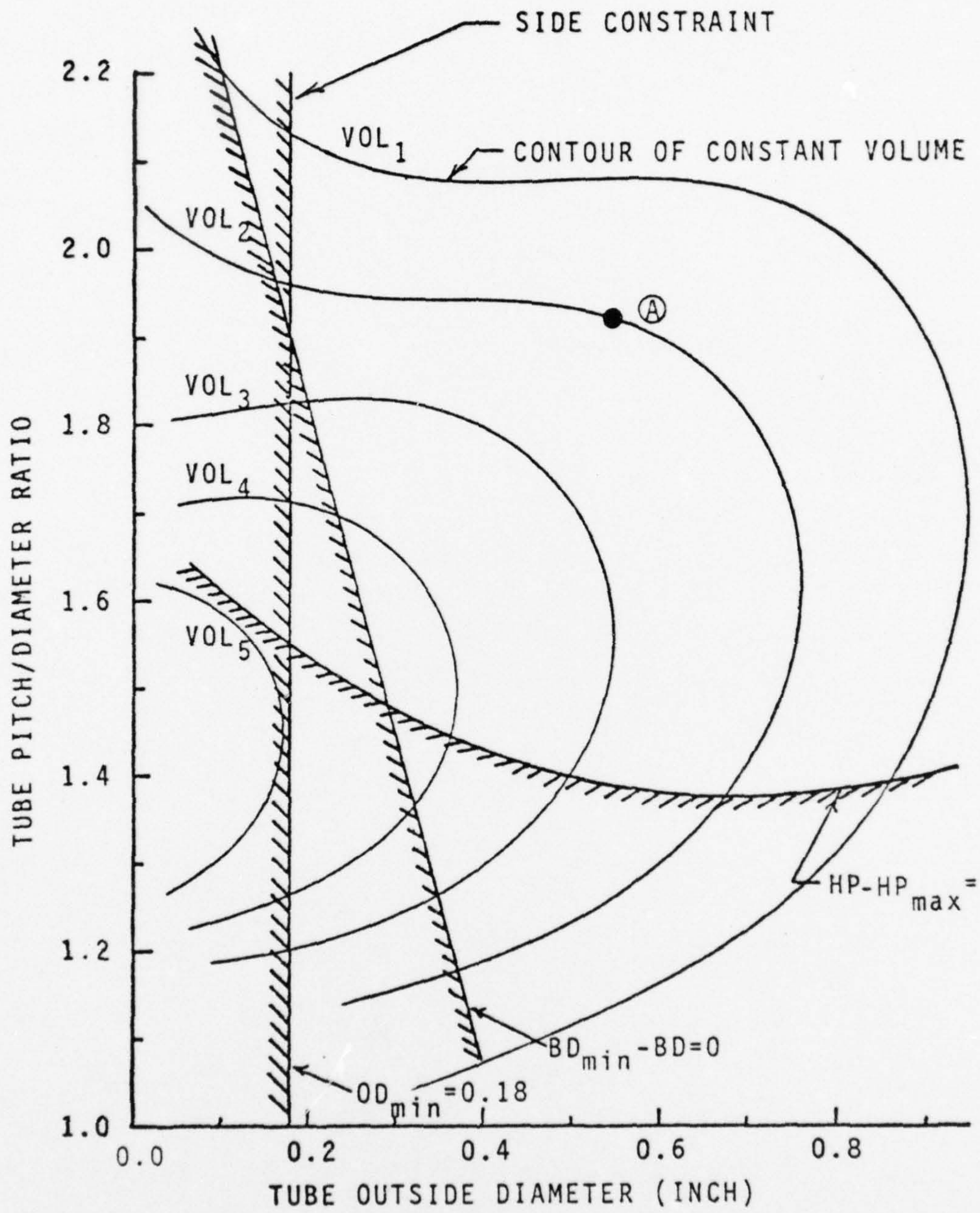

FIGURE 2. Two-Variable Design Space Showing the Initial Design at Point Ⓐ .

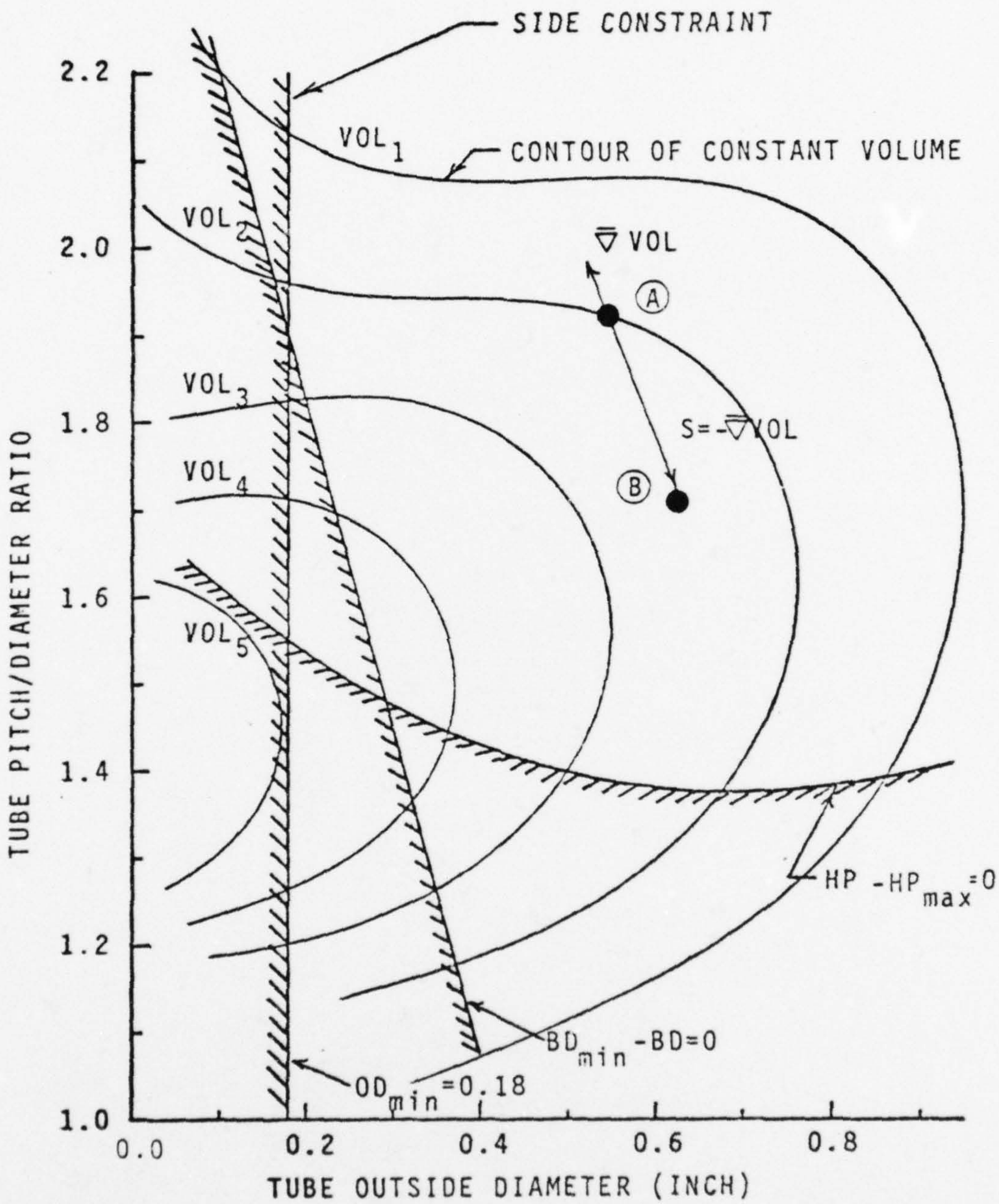

FIGURE 3. Two-Variable Design Space Showing the First Design Iteration

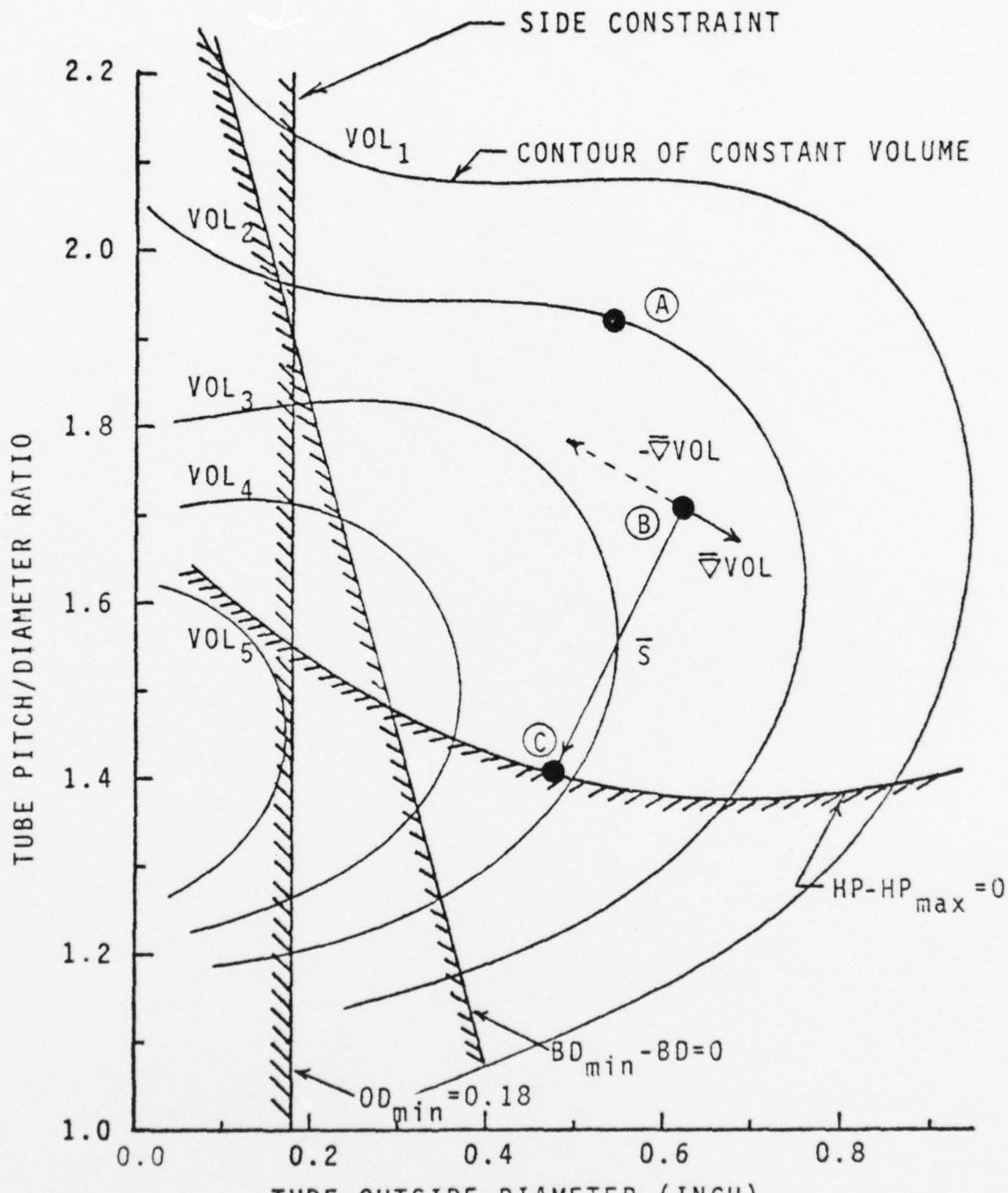

FIGURE 4. Two-Variable Design Space Showing the Second Design Iteration

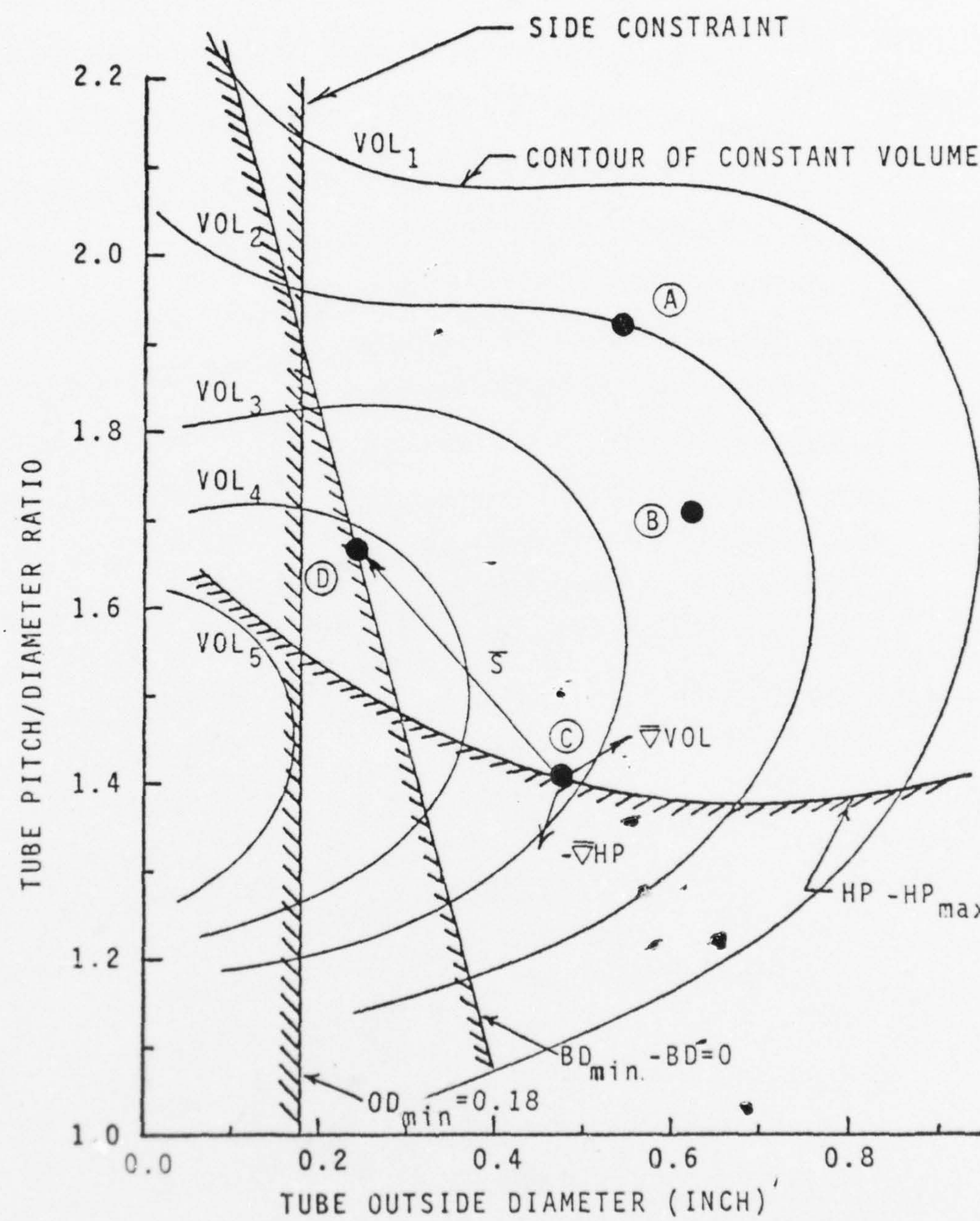

FIGURE 5. Two-Variable Design Space Showing the Third Design Iteration

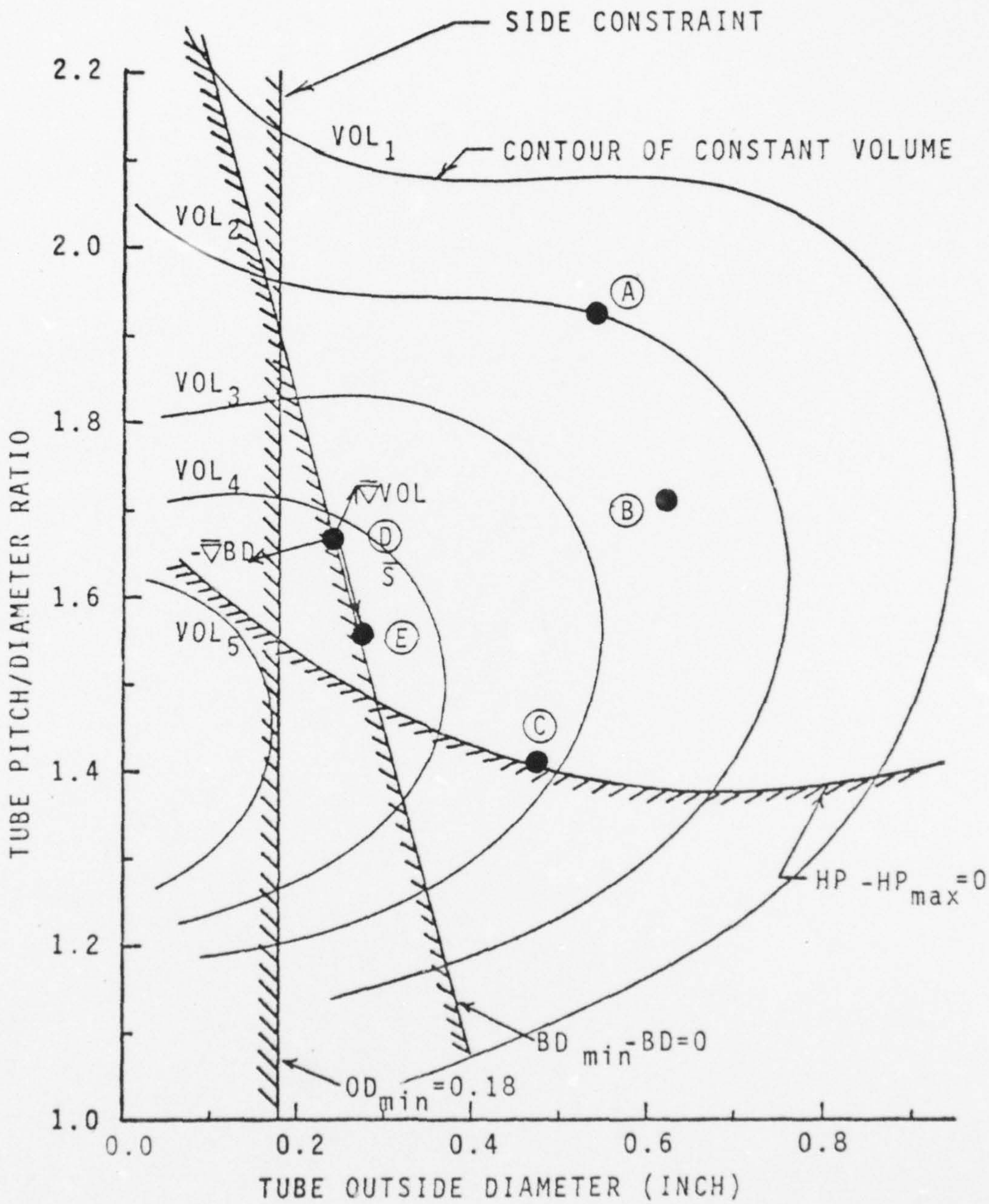

FIGURE 6. Two-Variable Design Space Showing the Fourth Design Iteration

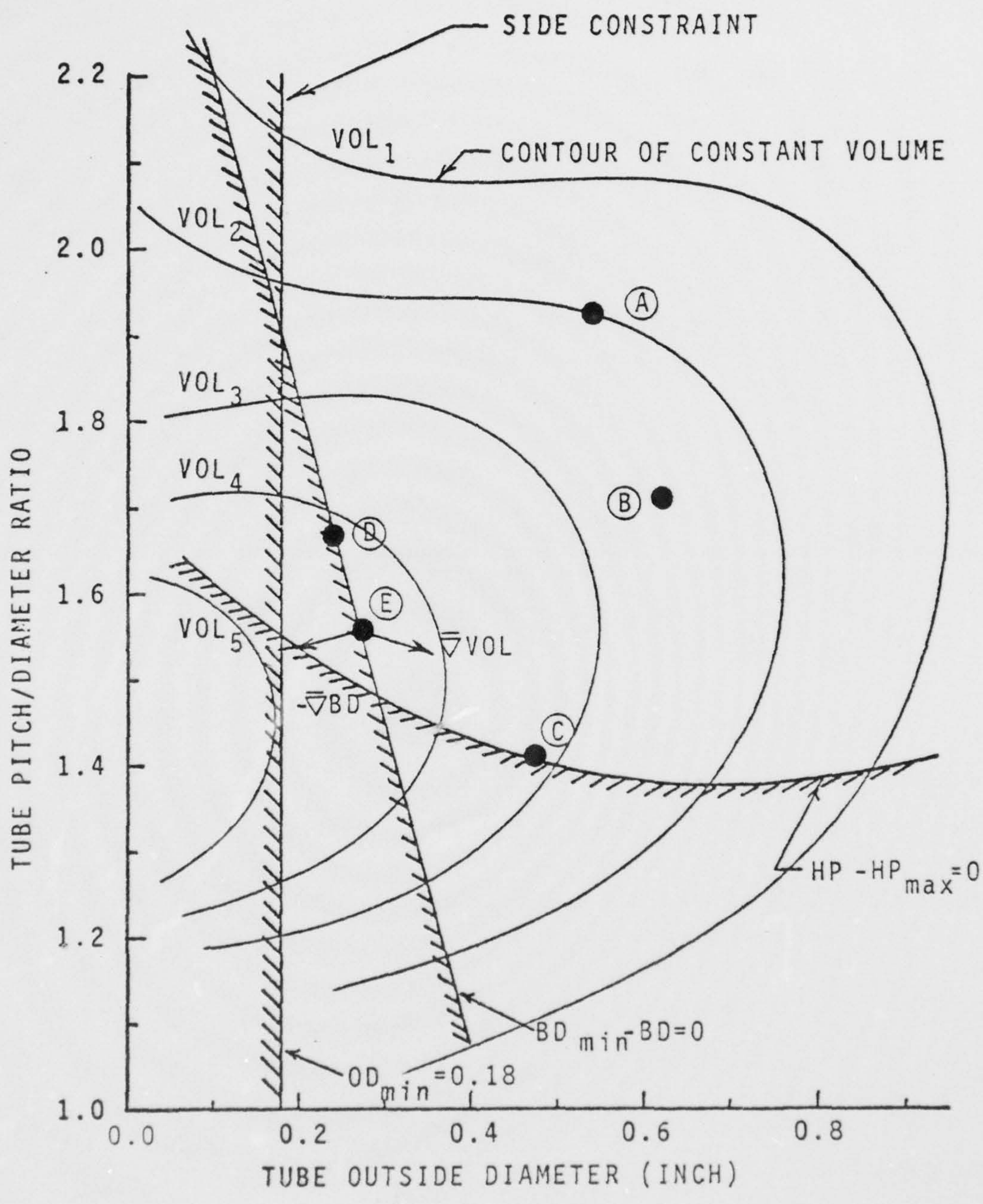

FIGURE 7. Two-Variable Design Space Showing the Fifth Design Iteration

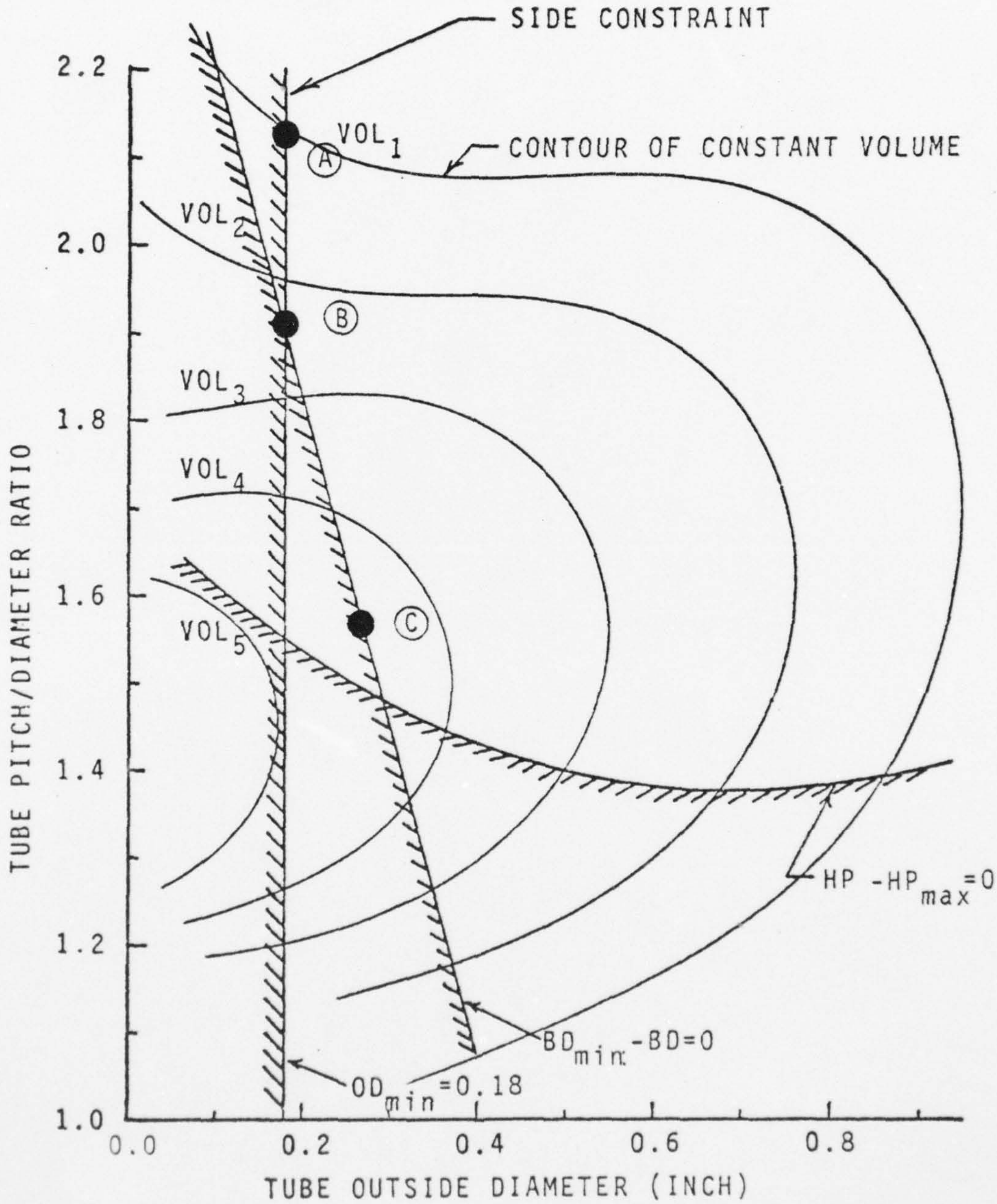

FIGURE 8. Two-Variable Design Space Showing the Need for Optimization Techniques

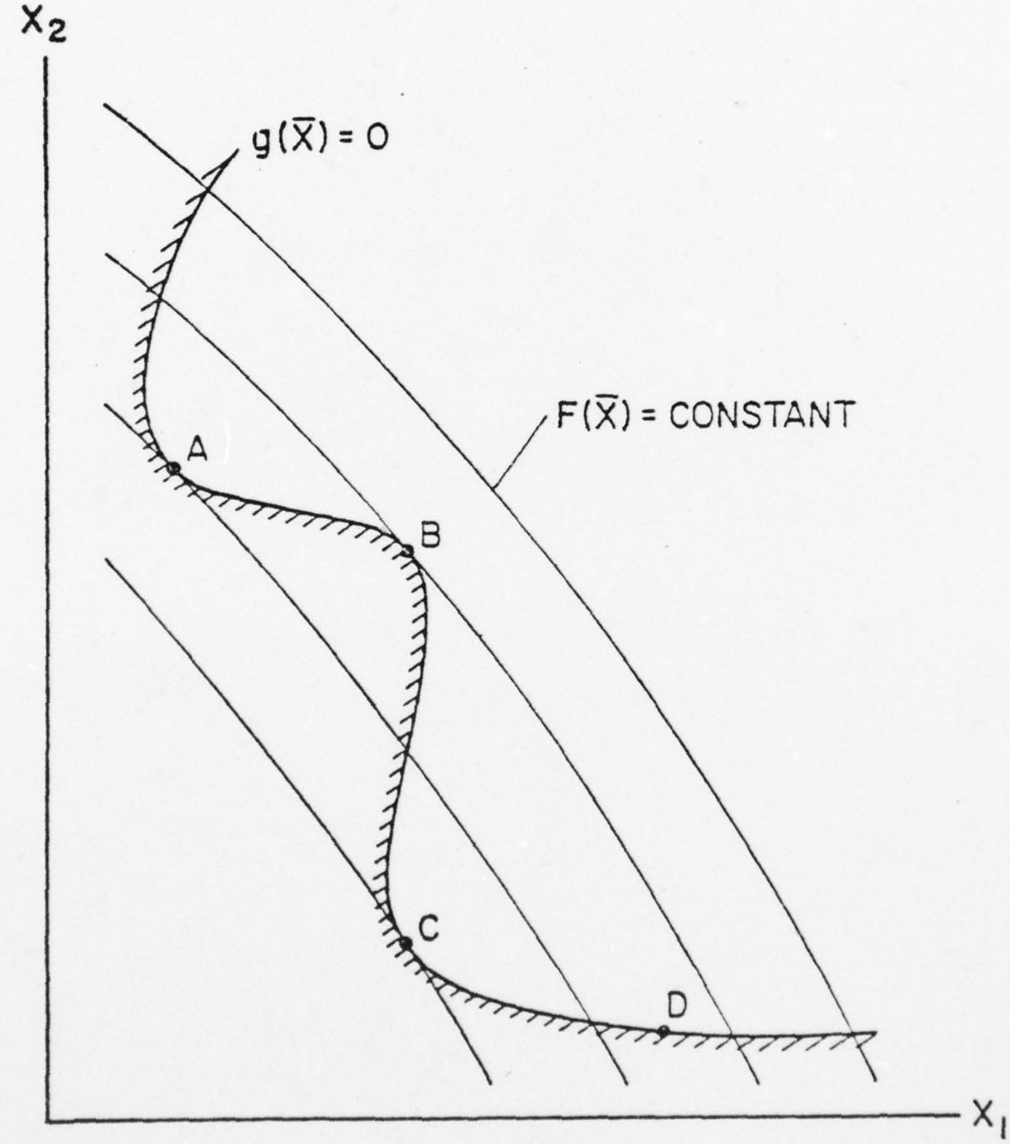

FIGURE 9. Two-Variable Design Space Showing Relative Minima for a Constrained Minimization Problem

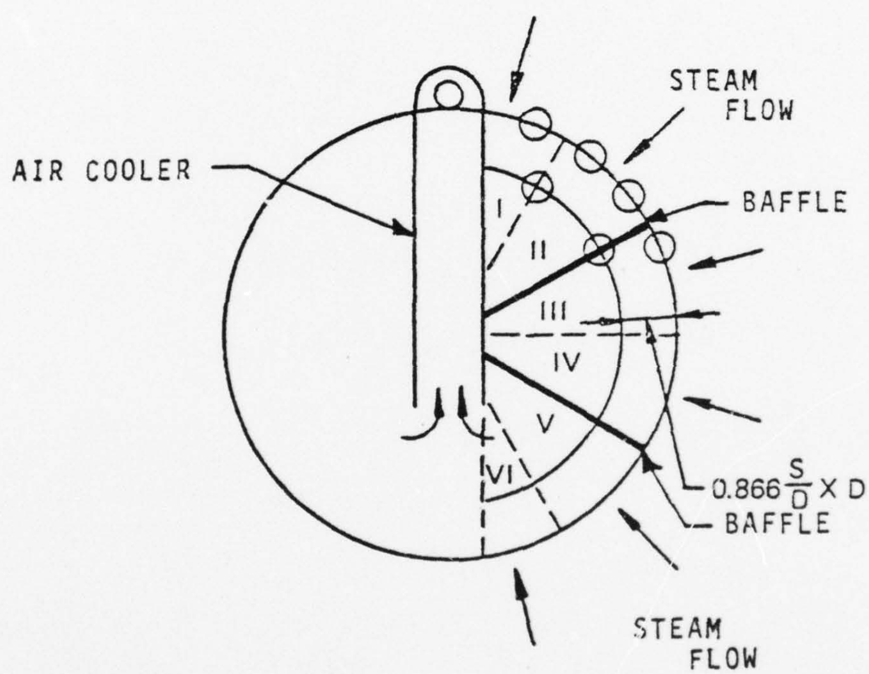

FIGURE 10. Circular Condenser Bundle Designed by ORCON1

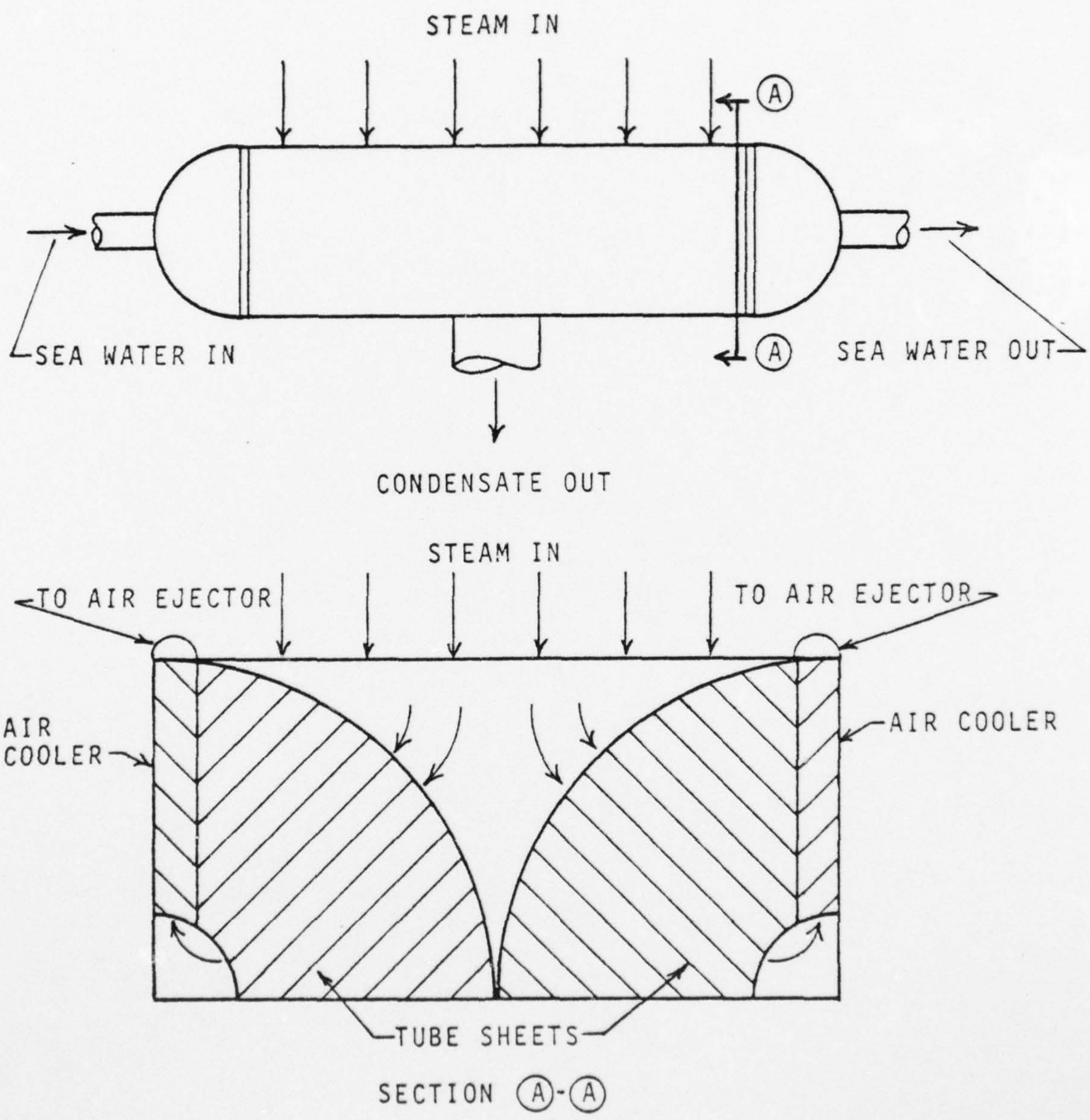

FIGURE 11. CVA 67 Main Condenser as Modeled by ORCON1 and OPCODE2

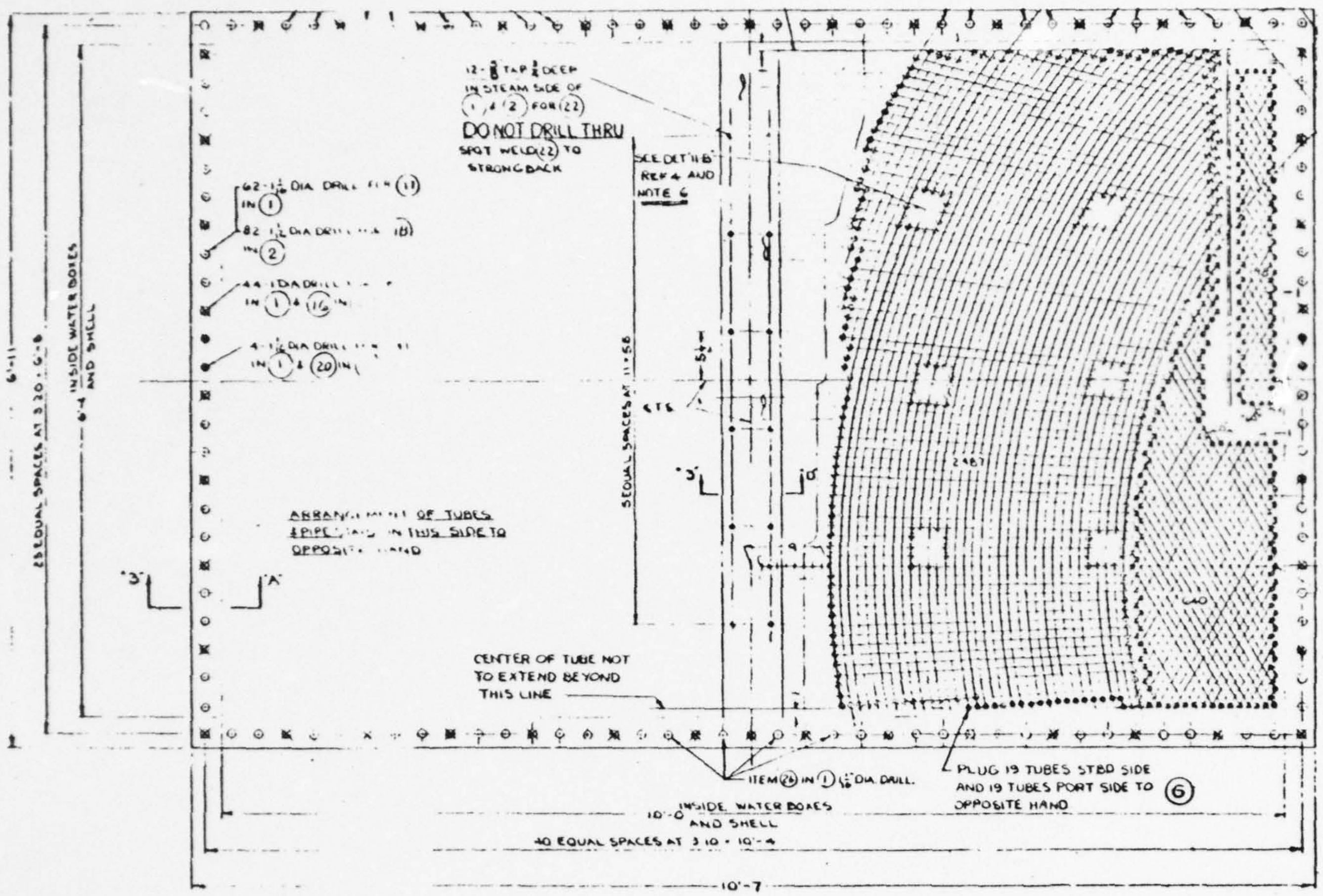

FIGURE 12. CVA 67 Main Condenser Tube Sheet

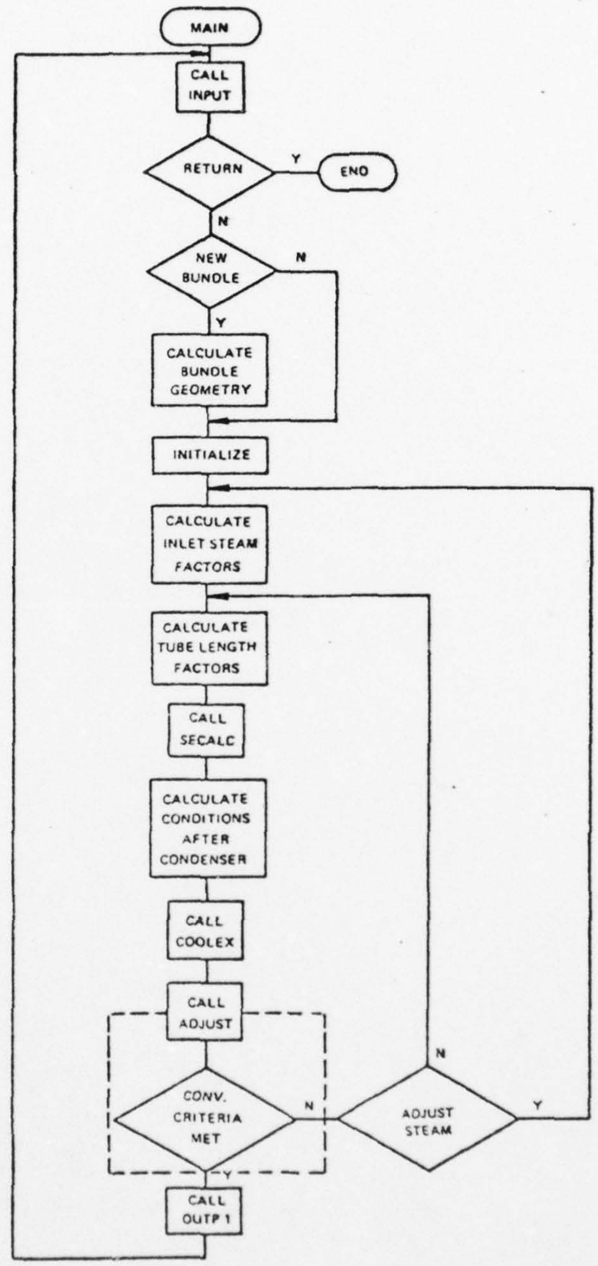

FIGURE 13. Flowchart from ORCON1

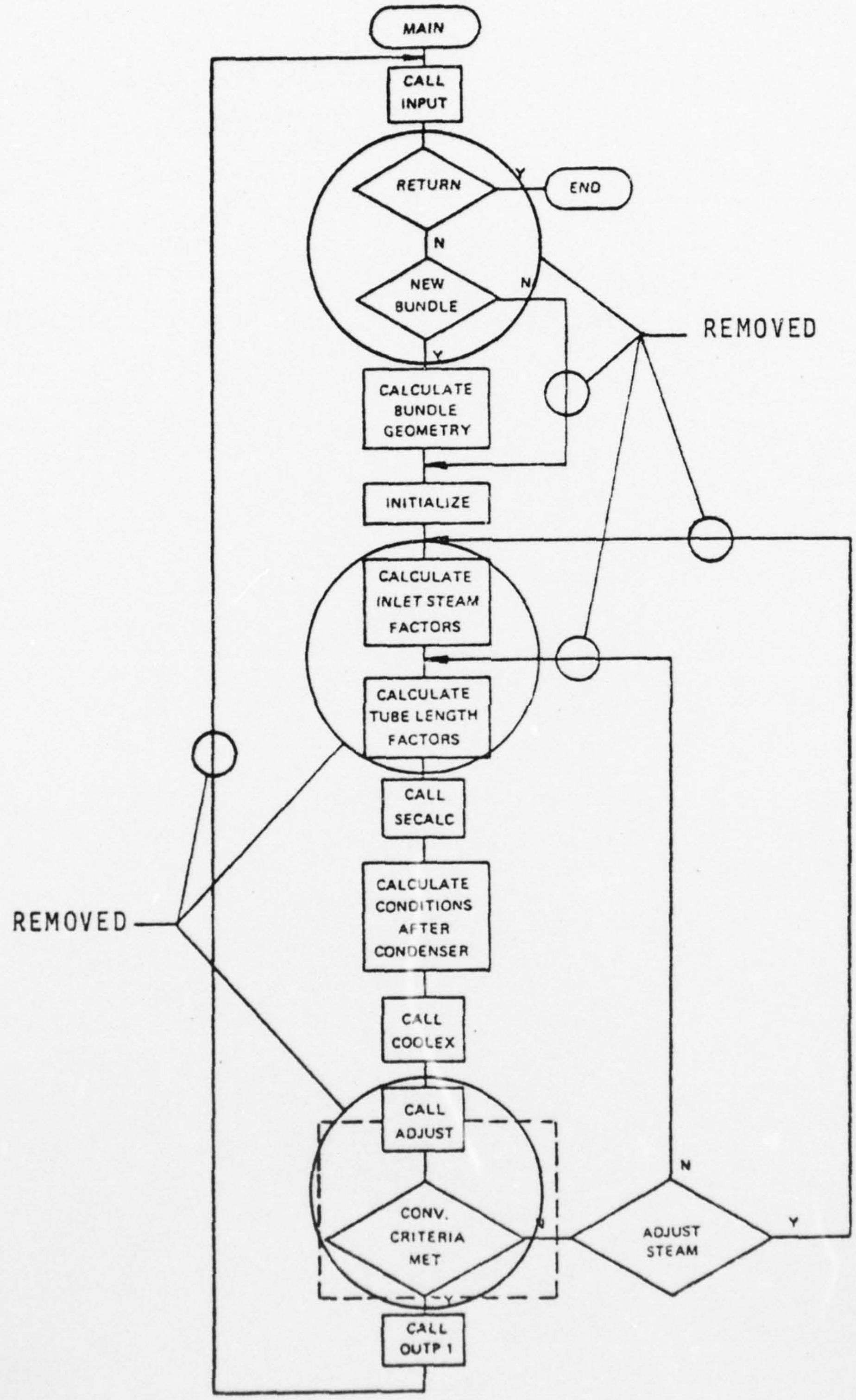

FIGURE 14. Flowchart Showing Modification of ORCON1 to OPCODE2

IX. TABLES

	TECHNICAL MANUAL	OPCODE1	DEVIATION (%)
Heat transfer area; ft^2	16,011	16,099	+0.55
Number of tubes	6,612	6,648	+0.54
Bundle diameter; ft	N/A	7.26	-
Heat rejected; BTU/hr	4.035×10^8	4.035×10^8	0.00
Overall heat transfer coefficient; BTU/(hr)(ft^2)(°F)	635	637	+0.31
Log mean temperature difference; °F	39.7	39.3	-1.01
Sea water temperature rise; °F	19.9	19.9	0.0
Terminal temperature difference; °F	30.53	30.2	-1.08
Sea water flow rate, gpm	40,565	40,645	+0.20
Tube-side pressure drop; ft. w.c.	16.3	12.4	-23.9

TABLE I. Verification of the CVA 67 Main Condenser Design Using OPCODE1

	TECHNICAL MANUAL	OPCODE1	DEVIATION (%)
Heat transfer area; ft^2	6,600	6,527	-1.11
Number of tubes	3,892	3,850	-1.08
Bundle diameter; ft	5.9	4.6	-22.1
Heat rejected; BTU/hr	2.05×10^8	2.047×10^8	-0.15
Overall heat transfer coefficient; BTU/(hr)(ft^2)(°F)	635	637	+0.31
Log mean temperature difference; °F	50.0	49.2	-1.6
Sea water temperature rise; °F	16.9	17.4	+2.96
Terminal temperature difference; °F	41.9	41.0	-2.15
Sea water flow rate; gpm	23,900	23,539	-1.51
Tube-side pressure drop; ft. w.c.	11.5	8.21	-28.6

TABLE II. Verification of the DE1040 Class of Main Condenser Using OPCODE1

PARAMETERS	TECHNICAL MANUAL VALUE	VALUE USING EISSENBERG's RELATION	DEVIATION FROM TECH. MANUAL (%)	VALUE USING KORODENSE RELATION	DEVIATION FROM TECH. MANUAL (%)
Heat transfer area; ft^2	16,011	16,008	-0.02	16,008	-0.02
Number of tubes	CONSTANT IN ALL CASES				
Bundle diameter; ft	N/A	10.23	N/A	10.23	N/A
Heat rejected; BTU/hr	4.035×10^8	2.937×10^8	-27	3.24×10^8	-20
Overall heat transfer coefficient; BTU/(hr)(ft^2)(°F)	635	504	-21	562	-11
Log mean temperature difference; °F	39.7	36.3	-8.6	36.0	-9.3
Sea water temperature rise; °F	19.9	14.4	-28	15.6	-22
Terminal temperature difference; °F	30.5	25.2	-17	25.6	-16
Sea water flow rate, gpm	40,565	40,341	-0.55	40,341	-0.55
Tube-side pressure drop, ft w.c	16.3	12.3	-25	12.3	-25
Exit steam vent rate as percentage of inlet steam	N/A	29	N/A	22	N/A

TABLE III. Verification of the CVA 67 Main Condenser Using OPCODE2

```
C V A ( 6 7 ) M A I N   C O N D E N S E R   D E S I G N

                          ***********************************
                          *                                 *
                          *     I N P U T   V A L U E S     *
                          *                                 *
                          ***********************************

TUBE INFORMATION
----------------

TUBE OD, IN.........     0.6250     TUBE ID, IN.........     0.5270     TUBE WALL, IN.......     0.0490
ABS. ROUGHNESS, FT.. 0.C000050     TUBE LENGTH, FT.....    14.8000     MAT'L. CORR. FACTOR         0.90
TUBE CLEAN. FACTOR..       0.85     NR. OF PASSES.......          1     MATERIAL IDENT......            3

SEA WATER INFORMATION
---------------------

INJECTION TEMP., F..        75.     SEA WATER VELC., FPS       9.00

INLET STEAM INFORMATION
-----------------------

AUX. STEAM, LB/HR...     11065.     MAIN STEAM, LB/HR...    418600.     TOTAL STEAM, LB/HR..    429665.
AUX. STEAM ENTHALPY       481.8     MAIN STEAM ENTHALPY       950.0     ADD'L. HEAT, BTU/HR     498000.
CHANGE, BTU/LB                      CHANGE, BTU/LB
SAT. TEMPERATURE, F       125.1     SAT. PRESSURE, PSIA      1.9646

                              TUBE MATERIAL CODE
                              ------------------

                            ADMIRALTY METAL... 1
                            ARSENICAL COPPER.. 1
                            ALUMINUM.......... 1
                            ALUMINUM BRASS.... 2
                            ALUMINUM BRONZE... 2
                            MUNTZ METAL....... 2
                            90-10 CU-NI....... 3
                            70-30 CU-NI....... 4
                            COLD ROLLED
                            LOW CARBON STEEL.. 5
                            STAINLESS STEELS
                              TYPE 410/430.... 6
                              TYPE 304/316.... 7
                              TYPE 329........ 8
                            TITANIUM.......... 9
```

TABLE IV. Input Parameters Used in OPCODE1 for Cases One Through Seven

```
C V A ( 6 7 ) M A I N   C O N D E N S E R   D E S I G N

                          ********************************
                          *                              *
                          * A N A L Y S I S  R E S U L T S *
                          *                              *
                          ********************************

TUBE INFORMATION
----------------

TUBE OD, IN.........    0.6250    TUBE ID, IN.........    0.5270    TUBE WALL, IN.......    0.0490
TUBE LENGTH, FT.....     14.80    NR. OF TUBES........    6648.1    MAT'L. CORR. FACTOR       0.90

SEA WATER INFORMATION
---------------------

INJECTION TEMP., F..       75.    SEA WATER VELO., FPS      9.00


INLET STEAM INFORMATION
-----------------------

AUX. STEAM, LB/HR...    11065.    MAIN STEAM, LB/HR...   418600.    TOTAL STEAM, LB/HR..   429665.
AUX. STEAM ENTHALPY      481.8    MAIN STEAM ENTHALPY      950.0    ADD'L. HEAT, BTU/HR    49800C.
CHANGE, BTU/LB                    CHANGE, BTU/LB
SAT. TEMPERATURE, F      125.1    SAT. PRESSURE, PSIA     1.9646

BUNDLE INFORMATION
------------------

BUNDLE DIAMETER, FT       7.26    TUBE SHEET A., FT**2     41.38    WATERBOX DEPTH, FT..      3.63
VOLUME, FT**3.......     926.8    OVERALL LENGTH, FT..     22.06    TUBE PITCH/DIAM.....    1.60CC
AREA RATIO..........     0.342

HEAT TRANSFER AND PUMPING INFORMATION
-------------------------------------

HEAT REJECTED..... 0.40350E 09    OVERALL U......  ...    637.21    LMTD, F.............     39.23
  BTU/HR                          BTU/(HR*FT**2*F)
S-W TEMP. RISE, F...     19.85    PINCH POINT, F .....     30.24    S-W FLOW RATE, CFS..    90.633
S-W FLOW RATE, GPM..  40645.22    PUMPING POWER.......    68836.    S-W PRESSURE DROP...     12.19
                                       FT*LBF/SEC                         FT WATER
HEAT TRANSFER AREA,    16099.2    PUMPING POWER, HP...    125.16
FT**2
```

TABLE V. Initial Design by OPCODE1 for Cases One Through Seven

CVA (67) MAIN CONDENSER DESIGN

ANALYSIS RESULTS

TUBE INFORMATION

TUBE OD, IN..........	0.7332	TUBE ID, IN..........	0.6869	TUBE WALL, IN.......	0.0231
TUBE LENGTH, FT.....	12.95	NR. OF TUBES.........	8860.6	MAT'L. CORR. FACTOR	0.99

SEA WATER INFORMATION

INJECTION TEMP., F..	75.	SEA WATER VELO., FPS	3.99

INLET STEAM INFORMATION

AUX. STEAM, LB/HR...	11065.	MAIN STEAM, LB/HR...	418600.	TOTAL STEAM, LB/HR..	429665.
AUX. STEAM ENTHALPY CHANGE, BTU/LB	481.8	MAIN STEAM ENTHALPY CHANGE, BTU/LB	950.0	ADD'L. HEAT, BTU/HR	498000.
SAT. TEMPERATURE, F	125.1	SAT. PRESSURE, PSIA	1.9646		

BUNDLE INFORMATION

BUNDLE DIAMETER, FT	9.83	TUBE SHEET A., FT**2	75.89	WATERBOX DEPTH, FT..	3.75
VOLUME, FT**3.......	1439.0	OVERALL LENGTH, FT..	20.45	TUBE PITCH/DIAM.....	1.6247
AREA RATIO..........	0.342				

HEAT TRANSFER AND PUMPING INFORMATION

HEAT REJECTED..... BTU/HR	0.40350E 09	OVERALL U...... ... BTU/(HR*FT**2*F)	465.10	LMTD, F.............	39.38
S-W TEMP. RISE, F...	19.78	PINCH POINT, F	30.31	S-W FLOW RATE, CFS..	90.987
S-W FLOW RATE, GPM..	40804.12	PUMPING POWER....... FT*LBF/SEC	10831.	S-W PRESSURE DROP... FT WATER	1.91
HEAT TRANSFER AREA, FT**2	22031.0	PUMPING POWER, HP...	19.69		

TABLE VI. Case One Optimization Results

AD-A049 953 NAVAL POSTGRADUATE SCHOOL MONTEREY CALIF F/G 13/10
MARINE STEAM CONDENSER DESIGN USING NUMERICAL OPTIMIZATION.(U)
DEC 77 C M JOHNSON
UNCLASSIFIED NPS69-77-002 NL

2 OF 2
AD A049953

END
DATE
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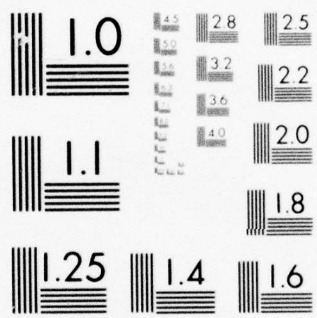
3-78
DDC



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

CVA (67) MAIN CONDENSER DESIGN

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******************************
* ANALYSIS RESULTS *
******************************
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TUBE INFORMATION

TUBE OD, IN.........	0.6250	TUBE ID, IN.........	0.5806	TUBE WALL, IN.......	0.0222
TUBE LENGTH, FT.....	15.07	NR. OF TUBES........	5831.9	MAT'L. CORR. FACTOR	0.99

SEA WATER INFORMATION

INJECTION TEMP., F..	75.	SEA WATER VELO., FPS	9.00

INLET STEAM INFORMATION

AUX. STEAM, LB/HR...	11065.	MAIN STEAM, LB/HR...	418600.	TOTAL STEAM, LB/HR..	429665.
AUX. STEAM ENTHALPY CHANGE, BTU/LB	481.8	MAIN STEAM ENTHALPY CHANGE, BTU/LB	950.0	ADD'L. HEAT, BTU/HR	498030.
SAT. TEMPERATURE, F	125.1	SAT. PRESSURE, PSIA	1.9646		

BUNDLE INFORMATION

BUNDLE DIAMETER, FT	6.63	TUBE SHEET A., FT**2	34.51	WATERBOX DEPTH, FT..	3.31
VOLUME, FT**3.......	788.9	OVERALL LENGTH, FT..	21.70	TUBE PITCH/DIAM.....	1.3456
AREA RATIO..........	0.360				

HEAT TRANSFER AND PUMPING INFORMATION

HEAT REJECTED..... BTU/HR	0.40350E 09	OVERALL U...... ... BTU/(HR*FT**2*F)	700.56	LMTD, F.............	40.05
S-W TEMP. RISE, F...	18.64	PINCH POINT, F	31.45	S-W FLOW RATE, CFS..	96.515
S-W FLOW RATE, GPM..	43283.21	PUMPING POWER...... FT*LBF/SEC	67115.	S-W PRESSURE DROP... FT WATER	11.16
HEAT TRANSFER AREA, FT**2	14381.5	PUMPING POWER, HP...	122.03		

TABLE VII. Case Two Optimization Results

CVA (67) MAIN CONDENSER DESIGN

ANALYSIS RESULTS

TUBE INFORMATION

TUBE OD, IN..........	0.6253	TUBE ID, IN.........	0.5790	TUBE WALL, IN.......	0.0232
TUBE LENGTH, FT.....	14.23	NR. OF TUBES........	13023.6	MAT'L. CORR. FACTOR	0.95

SEA WATER INFORMATION

INJECTION TEMP., F..	75.	SEA WATER VELO., FPS	6.95

INLET STEAM INFORMATION

AUX. STEAM, LB/HR...	11180.	MAIN STEAM, LB/HR...	766028.	TOTAL STEAM, LB/HR..	777208.
AUX. STEAM ENTHALPY CHANGE, BTU/LB	481.8	MAIN STEAM ENTHALPY CHANGE, BTU/LB	950.0	ADD'L. HEAT, BTU/HR	458000.
SAT. TEMPERATURE, F	125.1	SAT. PRESSURE, PSIA	1.9646		

BUNDLE INFORMATION

BUNDLE DIAMETER, FT	9.92	TUBE SHEET A., FT**2	77.28	WATERBOX DEPTH, FT..	3.75
VOLUME, FT**3.......	1655.1	OVERALL LENGTH, FT..	21.73	TUBE PITCH/DIAM.....	1.5847
AREA RATIO..........	0.359				

HEAT TRANSFER AND PUMPING INFORMATION

HEAT REJECTED..... BTU/HR	0.73361E 09	OVERALL U....... ... BTU/(HR*FT**2*F)	613.65	LMTD, F.............	39.38
S-W TEMP. RISE, F...	19.77	PINCH POINT, F	30.32	S-W FLOW RATE, CFS..	165.503
S-W FLOW RATE, GPM..	74221.44	PUMPING POWER....... FT*LBF/SEC	68765.	S-W PRESSURE DROP... FT WATER	6.67
HEAT TRANSFER AREA, FT**2	30344.4	PUMPING POWER, HP...	125.03		

TABLE VIII. Case Three Optimization Results

CVA (67) MAIN CONDENSER DESIGN

ANALYSIS RESULTS

TUBE INFORMATION

TUBE OD, IN..........	0.6283	TUBE ID, IN..........	0.5194	TUBE WALL, IN........	0.0545
TUBE LENGTH, FT.....	14.72	NR. OF TUBES........	6794.5	MAT'L. CORR. FACTOR	0.88

SEA WATER INFORMATION

INJECTION TEMP., F..	75.	SEA WATER VELC., FPS	9.00

INLET STEAM INFORMATION

AUX. STEAM, LB/HR...	11065.	MAIN STEAM, LB/HR...	418600.	TOTAL STEAM, LB/HR..	429665.
AUX. STEAM ENTHALPY CHANGE, BTU/LB	481.8	MAIN STEAM ENTHALPY CHANGE, BTU/LB	950.0	ADD'L. HEAT, BTU/HR	498000.
SAT. TEMPERATURE, F	125.1	SAT. PRESSURE, PSIA	1.9646		

BUNDLE INFORMATION

BUNDLE DIAMETER, FT	7.20	TUBE SHEET A., FT**2	40.68	WATERBOX DEPTH, FT..	3.60
VOLUME, FT**3.......	910.0	OVERALL LENGTH, FT..	21.91	TUBE PITCH/DIAM.....	1.5757
AREA RATIO..........	0.360				

HEAT TRANSFER AND PUMPING INFORMATION

HEAT REJECTED..... BTU/HR	0.40350E 09	OVERALL U....... ... BTU/(HR*FT**2*F)	625.09	LMTD, F.............	39.25
S-W TEMP. RISE, F...	20.00	PINCH POINT, F	30.09	S-W FLOW RATE, CFS..	89.974
S-W FLOW RATE, GPM..	40345.51	PUMPING POWER....... FT*LBF/SEC	68993.	S-W PRESSURE DROP... FT WATER	12.30
HEAT TRANSFER AREA, FT**2	16447.5	PUMPING POWER, HP...	125.42		

TABLE IX. Case Four Optimization Results

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C V A  ( 6 7 )  M A I N  C O N D E N S E R  D E S I G N

                         ********************************
                         * A N A L Y S I S  R E S U L T S *
                         ********************************

TUBE INFORMATION
----------------

TUBE OD, IN.........    0.6252    TUBE ID, IN.........     0.4358    TUBE WALL, IN.......   0.0947
TUBE LENGTH, FT.....    8.28      NR. OF TUBES........   13024.6     MAT'L. CORR. FACTOR    0.77

SEA WATER INFORMATION
---------------------

INJECTION TEMP., F..     75.      SEA WATER VELO., FPS      8.88

INLET STEAM INFORMATION
-----------------------

AUX. STEAM, LB/HR...   11065.     MAIN STEAM, LB/HR...   418600.     TOTAL STEAM, LB/HR..   429665.
AUX. STEAM ENTHALPY      481.8    MAIN STEAM ENTHALPY      950.0     ADD'L. HEAT, BTU/HR    458000.
CHANGE, BTU/LB                    CHANGE, BTU/LB
SAT. TEMPERATURE, F    125.1      SAT. PRESSURE, PSIA      1.9646

BUNDLE INFORMATION
------------------

BUNDLE DIAMETER, FT      9.91     TUBE SHEET A., FT**2    77.18      WATERBOX DEPTH, FT..     3.75
VOLUME, FT**3.......  1100.1      OVERALL LENGTH, FT..    15.76      TUBE PITCH/DIAM.....   1.5838
AREA RATIO..........     0.360

HEAT TRANSFER AND PUMPING INFORMATION
-------------------------------------

HEAT REJECTED..... 0.40350E 09    OVERALL U...... ...     542.40     LMTD, F.............    42.13
      BTU/HR                      BTU/(HR*FT**2*F)
S-W TEMP. RISE, F...    15.02     PINCH POINT, F .....     35.07     S-W FLOW RATE, CFS..   119.770
S-W FLOW RATE, GPM..  53711.99    PUMPING POWER.......   69010.      S-W PRESSURE DROP...     9.24
                                          FT*LBF/SEC                        FT WATER
HEAT TRANSFER AREA,   17655.9     PUMPING POWER, HP...    125.47
FT**2
```

TABLE X. Case Five Optimization Results

CVN (67) MAIN CONDENSER DESIGN

ANALYSIS RESULTS

TUBE INFORMATION

TUBE OD, IN.........	0.6322	TUBE ID, IN.........	0.5850	TUBE WALL, IN........	0.0236
TUBE LENGTH, FT.....	14.12	NR. OF TUBES........	6788.5	MAT'L. CORR. FACTOR	0.55

SEA WATER INFORMATION

INJECTION TEMP., F..	75.	SEA WATER VELO., FPS	7.52

INLET STEAM INFORMATION

AUX. STEAM, LB/HR...	11065.	MAIN STEAM, LB/HR...	418600.	TOTAL STEAM, LB/HR..	429665.
AUX. STEAM ENTHALPY CHANGE, BTU/LB	431.8	MAIN STEAM ENTHALPY CHANGE, BTU/LB	950.0	ADD'L. HEAT, BTU/HR	456000.
SAT. TEMPERATURE, F	125.1	SAT. PRESSURE, PSIA	1.9646		

BUNDLE INFORMATION

BUNDLE DIAMETER, FT	7.32	TUBE SHEET A., FT**2	42.14	WATERBOX DEPTH, FT..	3.66
VOLUME, FT**3.......	917.0	OVERALL LENGTH, FT..	21.45	TUBE PITCH/DIAM.....	1.5986
AREA RATIO..........	0.351				

HEAT TRANSFER AND PUMPING INFORMATION

HEAT REJECTED..... BTU/HR	0.40350E 09	OVERALL U...... ... BTU/(HR*FT**2*F)	657.44	LMTD, F.............	35.90
S-W TEMP. RISE, F...	18.90	PINCH POINT, F	31.20	S-W FLOW RATE, CFS..	95.230
S-W FLOW RATE, GPM..	42706.62	PUMPING POWER...... FT*LBF/SEC	44991.	S-W PRESSURE DROP... FT WATER	7.58
HEAT TRANSFER AREA, FT**2	15864.2	PUMPING POWER, HP...	81.80		

TABLE XI. Case Six Optimization Results

CVA (67) MAIN CONDENSER DESIGN

ANALYSIS RESULTS

TUBE INFORMATION

TUBE OD, IN.........	0.6262	TUBE ID, IN.........	0.5800	TUBE WALL, IN.......	0.0231
TUBE LENGTH, FT.....	15.18	NR. OF TUBES........	13022.7	MAT'L. CORR. FACTOR	0.55

SEA WATER INFORMATION

INJECTION TEMP., F..	75.	SEA WATER VELC., FPS	7.87

INLET STEAM INFORMATION

AUX. STEAM, LB/HR...	11202.	MAIN STEAM, LB/HR...	871545.	TOTAL STEAM, LB/HR..	882747.
AUX. STEAM ENTHALPY CHANGE, BTU/LB	481.8	MAIN STEAM ENTHALPY CHANGE, BTU/LB	950.0	ADD'L. HEAT, BTU/HR	498000.
SAT. TEMPERATURE, F	125.1	SAT. PRESSURE, PSIA	1.9646		

BUNDLE INFORMATION

BUNDLE DIAMETER, FT	9.92	TUBE SHEET A., FT**2	77.30	WATERBOX DEPTH, FT..	3.75
VOLUME, FT**3.......	1757.2	OVERALL LENGTH, FT..	22.68	TUBE PITCH/DIAM.....	1.5825
AREA RATIO..........	0.360				

HEAT TRANSFER AND PUMPING INFORMATION

HEAT REJECTED..... BTU/HR	0.833386E 09	OVERALL U....... ... BTU/(HR*FT**2*F)	655.53	LMTD, F.............	39.26
S-W TEMP. RISE, F...	19.77	PINCH POINT, F	30.22	S-W FLOW RATE, CFS..	188.078
S-W FLOW RATE, GPM..	84345.50	PUMPING POWER....... FT*LBF/SEC	103019.	S-W PRESSURE DROP... FT WATER	6.79
HEAT TRANSFER AREA, FT**2	32409.1	PUMPING POWER, HP...	187.31		

TABLE XII. Case Seven Optimization Results

	INITIAL VALUE	VALUE AT OPTIMUM	CHANGE (%)
Heat transfer area; ft^2	16,008	18,290	+14
Number of tubes	6,612	6,612	0.0
Bundle diameter; ft	10.23	8.95	-13
Heat rejected; BTU/hr	3.241×10^8	3.916×10^8	+21
Overall heat transfer coefficient BTU/(hr)(ft^2)(°F)	562	625	+11
Log mean temperature difference; °F	36	34	-5.6
Sea water temperature rise; °F	15.6	13.7	-12
Terminal temperature difference; °F	25.6	24.6	-3.9
Sea water flow rate; gpm	40,341	54,479	+35
Tube-side pressure drop; ft. w.c.	12.3	-	-
Tube length; ft	14.8	16.9	+14
Tube outside diam.; in.	0.625	0.625	0.0
Tube inside diam.; in.	0.527	0.581	+10
Tube wall; in.	0.049	0.022	-55
S-W velocity; fps	9.0	10.0	+11
Pitch/diameter	1.6	1.4	-13
Exit steam; % of input	21	5	-76
Pumping power; ft·lb/sec	35,409	58,290	+65
Condenser volume; ft^3	775	678	-13

TABLE XIII. Case Eight Initial Design and Optimization Results

	INITIAL VALUE	VALUE AT OPTIMUM	CHANGE (%)
Heat transfer area; ft^2	16,008	16.431	+2.6
Number of tubes	6,612	6,612	0.0
Bundle diameter; ft	10.23	8.95	-13
Heat rejected; BTU/hr	$3.241 x 10^8$	$3.924 x 10^8$	+21
Overall heat transfer coefficient, BTU/(hr)(ft^2)(°F)	562	751	+34
Log mean temperature difference; °F	36	32	-11
Sea water temperature rise; °F	15.6	13.1	-16
Terminal temperature difference; °F	25.6	21.6	-16
Sea water flow rate; gpm	40,341	54,479	+35
Tube-side pressure drop; ft. w.c.	12.3	-	-
Tube length; ft	14.8	15.2	+2.7
Tube outside diam.; in.	0.625	0.625	0.0
Tube inside diam.; in.	0.527	0.581	+10
Tube wall; in.	0.049	0.022	-55
S-W velocity; fps	9	10	+11
Pitch/diameter	1.6	1.4	-13
Exit steam; % of input	21	5	-76
Pumping power; ft·lb/sec	35,409	53,674	+52
Condenser volume; ft^3	775	609	-21

TABLE XIV. Case Nine Initial Design and Optimization Results

	INITIAL VALUE	VALUE AT OPTIMUM	CHANGE (%)
Heat transfer area; ft^2	16,008	19,808	+24
Number of tubes	6,612	6,612	0.0
Bundle diameter; ft	10.23	8.95	-13
Heat rejected; BTU/hr	2.937×10^8	3.910×10^8	+33
Overall heat transfer coefficient; BTU/(hr)(ft^2)(°F)	505	550	+8.9
Log mean temperature difference; °F	36	36	0.0
Sea water temperature rise; °F	14.4	14.2	-1.4
Terminal temperature difference; °F	25.2	26.3	+4.4
Sea water flow rate; gpm	40.341	54,479	+35
Tube-side pressure drop; ft. w.c.	12.3	16.0	+30
Tube length; ft	14.8	18.3	+24
Tube outside diam.; in.	0.625	0.625	0.0
Tube inside diam.; in.	0.527	0.581	+10
Tube wall; in.	0.049	0.022	+11
S-W velocity; fps	9	10	+11
Pitch/diameter	1.6	1.4	-13
Exit steam; % of input	29	5	-83
Pumping power; ft·lb/sec	35,409	62,059	+75
Condenser volume; ft^3	775	734	-5.3

TABLE XV. Case Ten Initial Design and Optimization Results

APPENDIX A

DEVELOPMENT OF THE ANALIZ SUBROUTINE FOR OPCODE1

OPCODE1 was based on the HEI/DDS method of calculation of heat transfer and thermodynamic parameters.

The following equations are used in the design of a condenser using the HEI/DDS method.

$$U_c = F_1 F_2 F_3 C\sqrt{V} \tag{A-1}$$

$$Q = U_c \, A_H \, \Delta T_{LM} \tag{A-2}$$

$$Q = W \, \Delta h \tag{A-3}$$

$$Q = 500\, G\, (t_o - t_i) \tag{A-4}$$

$$\Delta T_{LM} = \frac{t_o - t_i}{\ln\left(\frac{t_s - t_i}{t_s - t_o}\right)} \tag{A-5}$$

$$A_H = L\, N\, s \tag{A-6}$$

$$G = Ng\, V \tag{A-7}$$

$$k = s/g \tag{A-8}$$

The ANALIZ subroutine of OPCODE1 was divided into three sections: input, analysis and output. The correct section

of ANALIZ was entered by testing for the value of ICALC that was passed from COPES to ANALIZ.

When ICALC = 1, the input section of ANALIZ was entered and the input variables and problem identification were read. The input section had the capability to default the latent heat of vaporization to 950 BTU per pound as specified by reference [2] and to calculate either the saturation temperature or the saturation pressure depending on which value was not read in on the data card.

When COPES set ICALC = 2, the analysis section of ANALIZ was entered and the calculation of the outside area of a condenser tube per foot of tube length was made:

$$s = \pi D \quad [\frac{ft^2}{ft}] .$$

The rate of flow, in gallons per minute, through a condenser tube at a velocity of one foot per second was then made:

$$G1 = (\frac{\pi}{4}) \ (d^2) \ (60 \times 7.481) = 448.46(\frac{\pi}{4})d^2$$

$$[\frac{ft}{sec}][ft^2][\frac{sec}{min}][\frac{gal}{ft^3}] = [\frac{gal}{min}] .$$

The value of C in equation (A-1) was assumed to be a constant 270 when in fact, C was weakly dependent on tube outside diameter. With this assumption, the uncorrected heat transfer coefficient was calculated as:

$$U = C\sqrt{V} \quad [\frac{BTU}{hr\cdot ft^2\cdot °F}] \ .$$

A call was then made to subroutine MATFAC to find the new value of the material correction factor, F2, based on the current value of tube wall thickness. The temperature correction factor, F_3, was found with the function subroutine TEMFAC.

The data from Figure 1 of reference [2] was implemented in TEMFAC and a value of F_3 as a function of injection temperature was retrieved using subroutine INTRPL, a systems supplied interpolator.

The fouling factor, F_1, was set to 0.85 in accordance with references 1 and 2 during the input section of ANALIZ.

The corrected value of the overall heat transfer coefficient was calculated:

$$U_c = F_1 \ F_2 \ F_3 \ U \ .$$

The original form of equation (A-4) was:

$$Q = 60 \ W \ C_p \ G \ (t_o - t_i) \ .$$

For sea water, the following value of $60 \ W \ C_p$ was calculated:

$$60(W \ C_p)_{S\text{-}W} = (60)(8.55)(0.94) = 482$$

while, for fresh water, 60 W C_p was calculated as:

$$60(W\ C_p)_{F-W} = (60)(8.33)(1.0) = 500 .$$

Reference [2] recommends the use of 60 W C_p = 500 in keeping with industry standards. This approximation will induce an error of approximately one-half percent.

Be setting equation (A-2) equal to equation (A-4) and substituting for values of G, A_H and ΔT_{LM}, the following relation was obtained:

$$\ln \left[\frac{t_s - t_i}{t_s - t_o}\right] \approx \frac{U_c\ L\ K}{500\ V} \qquad \text{(A-9)}$$

which can be written as:

$$\frac{t_s - t_i}{t_s - t_o} \approx e^a$$

where:

$$a \equiv \frac{U_c\ L\ K}{500\ V}$$

Equation (A-9) was solved for the cooling water outlet temperature

$$t_o = t_s - \frac{t_s - t_i}{e^a} .$$

The sea water temperature rise and the pinch point were calculated, as was the initial temperature difference. All the factors were now available for the calculation of the logarithmic mean temperature difference, ΔT_{LM}, using equation (A-5).

The input heat load was divided into the auxiliary steam flow, main steam flow, and heat from other sources.

The auxiliary and main steam flows were multiplied by their respective changes in latent heat, Δh, and summed with the heat from other sources to yield the total heat input, Q.

If an input value for Δh is not read in for either auxiliary or main steam flow, the default value of 950 BTU per pound, specified by reference [2], is used.

With the value of Q, equation (A-4) was utilized to calculate the required flow rate of cooling water, G. With the value of G known, the heat transfer area, A_H, was found using equations (A-6), (A-7) and (A-8):

$$A_H = \frac{L\ G\ K}{V} .$$

The heat rejected to the cooling water was found by using equation (A-2).

The next portion of ANALIZ was devoted to the calculation of bundle geometry. The call to subroutine GEOM yielded a condenser design of circular bundle cross section

with a 12 inch diameter void along the longitudinal centerline to serve as a header for the removal of noncondensable gasses by an air ejector. The rows of tubes were filled from the inner void and were concentric to the center void. Partial tubes were permitted in order to simplify the algorithm and the final, outermost row was only partially filled. The bundle radius was calculated with no allowance for circumferential steam lanes, since it is beyond the capability of the HEI/DDS method to provide for steam lanes.

It was assumed that the waterboxes were hemispherical caps on the ends of the cylindrical bundle. The waterboxes may not be any deeper than 45 inches [2] and logic was included to ensure that this specification was met.

The ratio of tube sheet material removed for tube installation to original undrilled tube sheet area was calculated and used as a design constraint during the optimization process. Reference [2] requires that the ratio calculated must be less than or equal to 0.24 to allow for adequate tube sheet strength.

A hotwell capacity capable of receiving the condensate from one minute of full power operation is specified by reference [2]. This value was calculated as the product of the specific volume of the incoming steam and the steam flow rate.

The calls to subroutines FRIFLAC and PRSDRP found the factors required for the calculation of tube side pressure drop and pumping power.

Total condenser volume was the sum of the tube bundle volume, the waterbox volume, and the hotwell volume with the individual watervoxes treated as spherical caps.

The final step in the analysis section of subroutine ANALIZ was to define the objective function with any necessary weighting factors as described in Chapter II.

COPES repeatedly enters the ANALIZ subroutine with ICALC = 2 during the optimization process — often on the order of hundreds of times. Therefore, no WRITE statements were included in the analysis section. All output was performed within the output portion of ANALIZ, a region that is entered only when the optimization process is terminated and ICALC is set equal to three.

APPENDIX B

DEVELOPMENT OF SUPPORTING SUBROUTINES FOR OPCODE1

In this appendix, the subroutines that were utilized during the execution of ANALIZ in OPCODE1 are briefly described.

FRIFAC

This subroutine iteratively solved the transcendental Colebrook equation [17]:

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{2.51}{Re\sqrt{f}} + \frac{\varepsilon}{3.7d}\right)$$

for the value of the internal friction factor for tube flow. FRIFAC was valid for the range

$$0.01 \leq f \leq 0.10 .$$

This method was chosen over the simpler Blasius equation because of the inclusion of the desirable dependence on the relative roughness, ε/d, in the Colebrook equation.

GEOM

This subroutine calculated bundle geometry. The condenser bundle was assumed to have a 12 inch central void along the longitudinal centerline with the rows of tubes in concentric rows about the void. The void served as a

header for the venting of noncondensable gasses. The rows were filled from the inside out; partial tubes were permitted and the outermost row was unfilled.

PRSDRP

This subroutine calculated the cooling water pressure drop through the condenser bundle. The development of this subroutine was thoroughly discussed in Chapter III and will not be repeated here.

DENSE

This subroutine calculated the density of water as a function of temperature with the relation from reference [27]:

$$\rho = 63.8 - 0.01781\, t + 1.132 \times 10^{-5}\, t^2 - 6.786 \times 10^{-8}\, t^3 .$$

Based on the assumption made for determining the coefficient for equation (A-4) in Appendix A, the relation given above was used for the sea water as well as the steam and condensate densities.

For the calculation of cooling water density, the numerical average of the cooling water injection temperature and the cooling water overboard temperature was used.

PSATFN

This function subroutine calculated the saturation pressure of steam as a function of the saturation temperature,

in degrees Rankine, using the relation from reference [3]:

$$\ln P_s = 14.150119 - \frac{6452.562}{T_s} - \frac{837533.21}{T_s^{\,2}} \quad \text{(B-1)}$$

TEMFAC

The retrieval of the temperature correction factor, F_3, was performed in this function subroutine. The data presented in Figure SF-2 of reference [1] was implemented in tabular form and was retrieved as a function of cooling water injection temperature by a call to the library supplied interpolation subroutine, INTRPL.

TSATFN

This function subroutine calculated the saturation temperature as a function of saturation pressure by solving equation (B-1) for T_s.

MATFAC

This subroutine retrieved the material correction factor, F_2, as a function of wall thickness and tube material. The data presented in Figure ST-1 of reference [1] was in tabular form and was retrieved using the library supplied interpolation subroutine, INTRPL.

APPENDIX C

USER'S MANUAL FOR OPCODE 1

This Appendix describes the data cards required for the use of OPCODE1. A complete optimization run is included as Appendix D.

The data is divided into the COPES/CONMIN program section and the HEI/DDS-based condenser design program section.

The COPES data is segmented into "blocks" for convenience. All formats are alphanumeric for TITLE, END, and STOP cards, F10 for real data and I10 for integer data. Comment cards may be inserted anywhere in the data stack prior to the END card and are identified by a dollar sign ($) in column 1. The COPES data stack must terminate with an end card containing the word "END" in columns 1-3.

The analysis data is also segmented into blocks for convenience and must immediately follow the "END" card. No comment cards are permitted and the analysis data stack must terminate with the word "STOP" in columns 1-4.

It should be noted that only the information for using OPCODE1 for either a single analysis or for optimization is included in this User's Manual. Information pertaining to the use of the sensitivity analysis and the two-variable function space features of COPES can be found in reference [15].

DATA BLOCK A

DESCRIPTION: COPES Title Card

FORMAT: 20A4

TITLE CARD

REMARKS

1) Program is terminated by the word 'STOP' in columns 1-4.

DATA BLOCK B

DESCRIPTION: COPES Program Control Parameters

FORMAT: 7I10

1	2	3	4	5	6	7	8
NCALC	NDV			IPNPUT			

FIELD			CONTENTS
1	NCALC:		Calculation control
	0	-	Read input and stop. Data of blocks A-B is required. Remaining data is optional.
	1	-	One cycle through program. Data of blocks A-B is required. Remaining data is optional.
	2	-	Optimization. Data of blocks A-I is required. Remaining data is optional.
2	NDV:		Number of independent design variables in optimization or optimum sensitivity study.
5	IPNPUT:		Input print control
	0	-	Print card images plus formated print of input.
	1	-	Formated print of input only.
	2	-	No print of input.

REMARKS

1) Field 1 determines program execution.

2) Fields 3, 4, 6, 7, and 8 to be left blank for the OPCODE1 application of COPES/CONMIN.

DATA BLOCK C

DESCRIPTION: COPES Integer Optimization Control Parameters

FORMAT: 8I10

1	2	3	4	5	6	7	8
IPRINT	ITMAX	ICNDIR	NSCAL	ITRM	LINOBJ	NACMX1	NFDG

FIELD		CONTENTS
1	IPRINT:	Print control used in optimization program, CONMIN.
	0 -	No print during optimization.
	1 -	Print initial and final optimization information.
	2 -	Print above plus function value and design variable values at each iteration.
	3 -	Print above plus constraint values, direction vector and move parameter at each iteration.
	4 -	Print above plust gradient information.
	5 -	Print above plus each proposed design vector, objective function and constraints during the one-dimensional search.
2	ITMAX:	Maximum number of optimization iterations allowed. DEFAULT = 20.
3	ICNDIR:	Conjugate direction restart parameter. DEFAULT = NDV+1.
4	NSCAL:	Scaling parameter. GT.0 - Scale design variables to order of magnitude one every NSCAL iterations. LT.0 - Scale design variables according to scaling values input. DEFAULT = No scaling.
5	ITRM:	Number of subsequent iterations which must satisfy relative or absolute convergence criterion before optimization process is terminated. DEFAULT = 3.
6	LINOBJ:	Linear objective function identifier. If the optimization objective is known to be a linear function of the design variables, set LINOBJ = 1. DEFAULT = *Non-Linear*.
7	NACMX1:	One plus the maximum number of active constraints anticipated. DEFAULT = NDV+2.

DATA BLOCK C (Continued)

FIELD		CONTENTS
8	NFDG:	Finite difference gradient identifier.
	0 -	All gradient information is computed by finite difference.
	1 -	Gradient of objective is computed analytically. Gradients of constraints are computed by finite difference.
	2 -	All gradient information is computed analytically.

REMARKS

1) The value of NSCAL = 5 is suggested and ITRM = NACMX1 = 0 should be used.

2) The value of IPRINT may be reduced when the user is familiar with the optimization output.

DATA BLOCK D

DESCRIPTION: COPES Floating Point Optimization Program Parameters

FORMAT: 8F10

1	2	3	4	5	6	7	8
FDCH	FDCHM	CT	CTMIN	CTL	CTLMIN	THETA	PHI

Note: Two cards of data are read here.

FIELD		CONTENTS
1	FDCH:	Relative change in design variables in calculating finite difference gradients. DEFAULT = 0.01
2	FDCHM:	Minimum absolute step in finite difference gradient calculations. DEFAULT = 0.001.
3	CT:	Constraint thickness parameter. DEFAULT = -0.1.
4	CTMIN:	Minimum absolute value of CT considered in the optimization process. DEFAULT = 0.004.
5	CTL:	Constraint thickness parameter for linear and side constraints. DEFAULT = -0.01.
6	CTLMIN:	Minimum absolute value of CTL considered in the optimization process. DEFAULT = 0.001.
7	THETA:	Mean value of push-off factor in the method of feasible directions. DEFAULT = 1.0.
8	PHI:	Participation coefficient, used if one or more constraints are violated. DEFAULT = 5.0.

DATA BLOCK D (Continued)

FORMAT: 2F10

1	2	3	4	5	6	7	8
DELFUN	DABFUN						

FIELD		CONTENTS
1	DELFUN:	Minimum relative change in objective function to indicate convergence of optimization process. DEFAULT = 0.001.
2	DABFUN:	Minimum absolute change in objective function to indicate convergence of the optimization process. DEFAULT = 0.001 times the initial objective value.

DATA BLOCK E

DESCRIPTION: Total Number of Design Variables, Design Objective Identification and Sign on Design Objective.

FORMAT: 2I10, F10

1	2	3	4	5	6	7	8
NDVTOT	IOBJ	SGNOPT					

FIELD		CONTENTS
1	NDVTOT:	Total number of variables linked to the design variables. NDVTOT must be greater than or equal to NDV. This option allows two or more parameters to be assigned to a single design variable. The value of each parameter is the value of the design variable times a multiplier which may be different for each parameter. DEFAULT = NDV.
2	IOBJ:	Global variable number associated with objective function in optimization or optimum sensitivity analysis.
3	SGNOPT:	Sign used on objective of optimization to identify whether function is to be maximized or minimized. +1.0 indicates maximization. -1.0 indicates minimization. DEFAULT = -1.0.

DATA BLOCK F

DESCRIPTION: Design variable bounds, initial values and scaling factors.

FORMAT: 4F10

1	2	3	4	5	6	7	8
VLB	VUB	X	SCAL				

Note: Read one card for each of the NDV independent design variables.

FIELD		CONTENTS
1	VLB:	Lower bound on the design variable.
2	VUB:	Upper bound on the design variable.
3	X:	Initial value of the design variable. If X is non-zero, this will supercede the value initialized by subroutine ANALIZ.
4	SCAL:	Design variable scale factor. Not used if NSCAL.GE.0 in Block C.

DATA BLOCK G

DESCRIPTION: Design Variable Identification

FORMAT: 2I10, F10

1	2	3	4	5	6	7	8
NDSGN	IDSGN	AMULT					

Note: Read one card for each of the NDVTOT Design Variables.

FIELD		CONTENTS
1	NDSGN:	Design variable number associated with the variable.
2	IDSGN:	Global variable number associated with the variable.
3	AMULT:	Constant multiplier on the variable. The value of the variable will be the value of the design variable, NDSGN times AMULT. DEFAULT = 1.0.

DATA BLOCK H

DESCRIPTION: Number of constrained parameters.

FORMAT: I10

1	2	3	4	5	6	7	8
NCONS							

FIELD	CONTENTS	
1	NCONS:	Number of constraint sets in the optimization problem.

REMARKS

1) If two or more adjacent parameters in the Global common block have the same limits imposed, these are part of the same constraint set.

DATA BLOCK I

DESCRIPTION: Constraint Identification and Bounds.

FORMAT: 3I10

1	2	3	4	5	6	7	8
ICON	JCON	LCON					

Note: Read two cards for each of the NCONS constraint sets.

FIELD		CONTENTS
1	ICON:	First Global number corresponding to the constraint set.
2	JCON:	Last Global number corresponding to the constraint set. DEFAULT = ICON.
3	LCON:	Linear constraint identifier for this set of constrained variables. LCON = 1 indicates linear constraints. DEFAULT = 0 = Nonlinear constraint.

DATA BLOCK I (continued)

FORMAT: 4F10

1	2	3	4	5	6	7	8
BL	SCAL1	BU	SCAL2				

FIELD		CONTENTS
1	BL:	Lower bound on the constrained variables. Value less than -1.0E+15 is assumed unbounded.
2	SCAL1:	Normalization factor on lower bound. DEFAULT = Max of ABS(BL), 0.1.
3	BU:	Upper bound on the constrained variables. Value greater than 1.0E+15 is assumed unbounded.
4	SCAL2:	Normalization factor on upper bound. DEFAULT = Max of ABS(BU), 0.1.

REMARKS

1) The normalization factor should usually be defaulted.

DATA BLOCK P

DESCRIPTION: COPES data 'END' card.

FORMAT: 3A1

END CARD
END

FIELD	CONTENTS
1	The word 'END' in columns 1-3.

REMARKS

1) This card must appear at the end of the COPES data.

2) This ends the COPES input data.

OPCODE1 Analysis

Data for the condenser analysis follows the 'END' card in the COPES data deck. If the general design capability of COPES/CONMIN is not needed, the condenser analysis portion of OPCODE1 can be run in a stand-alone mode by using the following main program:

```
C     MAIN PROGRAM FOR STAND-ALONE CONDENSER
      ANALYSIS

C     INPUT SECTION
      ICALC=1
      CALL ANALIZ (ICALC)

C     EXECUTION SECTION
      ICALC=2
      CALL ANALIZ (ICALC)

C     OUTPUT SECTION
      ICALC=3
      CALL ANALIZ (ICALC)

      STOP
      END
```

DATA BLOCK AA

DESCRIPTION: Condenser Analysis Title Card

FORMAT: 20A4

TITLE CARD

DATA BLOCK   BB

DESCRIPTION: Objective Function Weighting Factor

FORMAT: E12.5

A

DATA BLOCK: CC

DESCRIPTION: Condenser Tube Input Data

FORMAT: 6F10, I2

1	2	3	4	5	6	7	8
SDO	SDI	XW	SDD	ALGTH	ROUGH		NPASS

FIELD		CONTENTS
1	SDO:	Tube outside diameter; inch.
2	SDI:	Tube inside diameter; inch.
3	XW:	Tube wall thickness; inch.
4	SDD:	Tube pitch to diameter ratio.
5	ALGTH:	Tube length, feet.
6	ROUGH:	Tube inside absolute roughness, foot.
8	NPASS:	Number of tube passes.

BLOCK DD

DESCRIPTION: Sea Water Information

FORMAT: 8F10.

1	2	3	4	5	6	7	8
VELC	T1						

FIELD		CONTENTS
1	VELC:	Sea water velocity in the condenser tubes, feet per second.
2	T1:	Sea water injection temperature, °F.

BLOCK EE

DESCRIPTION: Inlet Steam and Heat Load Information

FORMAT: 7F10

1	2	3	4	5	6	7	8
WMS	HFGMS	WAS	HFGAS	PSAT	TSAT	TRNSHT	

FIELD		CONTENTS
1	WMS:	Incoming main steam rate, pound per hour.
2	HFGMS:	Latent heat of condensation for main steam, BTU per pound.
3	WAS:	Incoming auxiliary steam rate, pound per hour
4	HFGAS:	Latent heat of condensation for auxiliary steam, BTU per pound.
5	PSAT:	Saturation pressure of incoming steam, pounds per square inch absolute.
6	TSAT:	Saturation temperature of incoming steam, degrees Fahrenheit.
7	TRNSHT:	Heat load from other sources, BTU per hour.

REMARKS

1) If no value for HFGMS or HFGAS is read in, these parameters will default to 950 BTU per pound.

2) Either PSAT or TSAT is to be specified.

DATA BLOCK FF

DESCRIPTION: Tube Material Identification

FORMAT: I10

1	2	3	4	5	6	7	8
IDMATL							

FIELD		CONTENTS
1	IDMATL:	Material identification from the following table.

TUBE MATERIAL CODE

ADMIRALTY METAL	1
ARSENICAL COPPER	1
ALUMINUM	1
ALUMINUM BRASS	2
ALUMINUM BRONZE	2
MUNTZ METAL	2
90-10 CU-NI	3
70-30 CU-NI	4
COLD ROLLED LOW CARBON STEEL	5
STAINLESS STEELS	
TYPE 410/430	6
TYPE 304/316	7
TYPE 329	8
TITANIUM	9

DATA BLOCK GG

DESCRIPTION: STOP Card

FORMAT: 4A1

STOP CARD
STOP

FIELD	CONTENTS
1	The word 'STOP' in columns 1-4.

REMARKS

1) This card must appear at the end of the analysis data.

2) This ends the analysis data.

APPENDIX D

SAMPLE OUTPUT FROM OPCODE1

```
CCCCCCC  CCCCOOO  PPPPPPP  EEEEEEE  SSSSSSS
C        O     O  P     P  E        S
C        O     O  P     P  E        S
C        O     O  PPPPPPP  EEEE     SSSSSSS
C        O     O  P        E              S
C        O     O  P        E              S
CCCCCCC  COOOOOO  P        EEEEEEE  SSSSSSS
```

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

CVA / CASE ONE /OBJ=POWER/MIN: POWER WITH CONSTANT QREJ/

CARD IMAGES OF CONTROL DATA

```
CARD                          IMAGE

  1)   CVA / CASE ONE /OBJ=POWER/MIN: POWER WITH CONSTANT QREJ/
  2)            2         5
  3)            1         40                          5                                  15
  4)
  5)
  6)                      18 -1.0
  7)   $  TUBE O.D., INCHES
  8)   0.625      1.25
  9)   $  TUBE I.D., INCHES
 10)   0.407      1.206
 11)   $  PITCH/DIAMETER RATIO
 12)   1.1         3.0
 13)   $  TUBE LENGTH, FEET
 14)   1.0         25.0
 15)   $  S-W VELOCITY IN TUBES, FPS
 16)   3.0         5.0
 17)            1         1
 18)            2         2
 19)            3         6
 20)            4         4
 21)            5         5
 22)            5
 23)   $  TUBE WALL THICKNESS, INCHES
 24)            7         7
 25)   0.022              0.109
 26)   $  CONDENSER DIAMETER, FEET
 27)            8         8
 28)   1.0                10.0
 29)   $  PINCH POINT, F
 30)           12        12
 31)   5.0                35.0
 32)   $  S-W TEMPERATURE RISE, F
 33)           13        13
 34)   5.0                20.0
 35)   $  RATIO OF TUBE HOLE AREA TO TUBE SHEET AREA WITHOUT DRILLED HOLES
 36)           16        16
 37)   0.1                0.36
 38)   END
```

TITLE:
CVA / CASE ONE /OBJ=POWER/MIN: POWER WITH CONSTANT QREJ/

```
CONTROL PARAMETERS:
CALCULATION CONTROL,                          NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,              NDV =    5
NUMBER OF SENSITIVITY VARIABLES,                NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,             N2VAR =    0
INPUT INFORMATION PRINT CODE,                IPNPUT =    0
SENSITIVITY PRINT CODE,                      IPSENS =    0
TWO-SPACE PRINT CODE,                        IP2VAR =    0
DEBUG PRINT CODE,                             IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE

GLOBAL VARIABLE NUMBER OF OBJECTIVE               =   18
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION)      = -0.1000E 01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT  ITMAX   ICNDIR   NSCAL   ITRM   LINOBJ  NACMX1  NFDG
  1      40       0        5       0      0      15       0

 FDCH            FDCHM           CT              CTMIN
 0.0             0.0             0.0             0.0

 CTL             CTLMIN          THETA           PHI
 0.0             0.0             0.0             0.0

 DELFUN          DABFUN
 0.0             0.0
```

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT

D. V. NO.	LOWER BOUND	UPPER BOUND	INITIAL VALUE	SCALE
1	0.62500E 00	0.12500E 01	0.0	0.0
2	0.40700E 00	0.12360E 01	0.0	0.0
3	0.11000E 01	0.30000E 01	0.0	0.0
4	0.10000E 01	0.25000E 02	0.0	0.0
5	0.30000E 01	0.90000E 01	0.0	0.0

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	MULTIPLYING FACTOR
1	1	1	0.10000E 01
2	2	2	0.10000E 01
3	3	6	0.10000E 01
4	4	4	0.10000E 01
5	5	5	0.10000E 01

CONSTRAINT INFORMATION

THERE ARE 5 CONSTRAINT SETS

ID	GLOBAL VAR. 1	GLOBAL VAR. 2	LINEAR ID	LOWER BOUND	NORMALIZATION FACTOR	UPPER BOUND	NORMALIZATION FACTOR
1	7	7	0	0.22000E-01	0.10000E 00	0.10900E 00	0.10900E 00
3	8	8	0	0.10000E 01	0.10000E 01	0.10000E 02	0.10000E 02
5	12	12	0	0.50000E 01	0.50000E 01	0.35000E 02	0.35000E 02
7	13	13	0	0.50000E 01	0.50000E 01	0.20000E 02	0.20000E 02
9	16	16	0	0.10000E 00	0.10000E 00	0.36000E 00	0.36000E 00

TOTAL NUMBER OF CONSTRAINED PARAMETERS = 5

DATA STORAGE REQUIREMENTS

REAL INPUT	REAL EXECUTION	REAL AVAILABLE	INTEGER INPUT	INTEGER EXECUTION	INTEGER AVAILABLE
54	473	5000	36	81	1000

```
CVA (67) MAIN CONDENSER DESIGN

                    ********************************
                    *                              *
                    *      I N P U T  V A L U F S  *
                    *                              *
                    ********************************

TUBE INFORMATICN
----------------

TUBE CD, IN.........    0.6250    TUBE ID, IN.........     0.5270    TUBE WALL, IN.......   0.0490
ABS. ROUGHNESS, FT.. 0.C000050    TUBE LENGTH, FT.....    14.8000    MAT'L. CORR. FACTCR      0.50
TUBE CLEAN. FACTCR..      0.85    NR. CF PASSES.......          1    MATERIAL ICENT......        3

SEA WATER INFORMATICN
---------------------

INJECTICN TEMP., F..       75.    SEA WATER VELC., FPS       9.00


INLET STEAM INFORMATION
-----------------------

AUX. STEAM, LB/HR...    11065.    MAIN STEAM, LB/HR...    418600.    TOTAL STEAM, LB/HR..  429665.
AUX. STEAM ENTHALPY      481.8    MAIN STEAM ENTHALPY       950.0    ADD'L. HEAT, BTU/HR   498000.
CHANGE, BTU/LB                    CHANGE, BTU/LB
SAT. TEMPERATURE, F      125.1    SAT. PRESSURE, PSIA      1.9646


                          TUBE MATERIAL CODE
                          ------------------

                        ADMIRALTY METAL... 1
                        ARSENICAL CCPPER.. 1
                        ALUMINUM.......... 1
                        ALUMINUM BRASS.... 2
                        ALUMINUM BRCNZE... 2
                        MUNTZ METAL....... 2
                        90-10 CU-NI....... 3
                        70-30 CU-NI....... 4
                        COLD ROLLED
                        LOW CARBCN STEEL.. 5
                        STAINLESS STEELS
                          TYPE 410/430.... 6
                          TYPE 304/316.... 7
                          TYPE 329........ 8
                        TITANIUM.......... 9
```

```
C V A  ( 6 7 )  M A I N  C O N D E N S E R  D E S I G N

                              ********************************
                              *                              *
                              *  A N A L Y S I S  R E S U L T S  *
                              *                              *
                              ********************************

TUBE INFORMATION
----------------

TUBE OD, IN.........   0.6250    TUBE ID, IN.........    0.5270    TUBE WALL, IN.......     0.0490
TUBE LENGTH, FT.....    14.80    NR. OF TUBES........    6648.1    MAT'L. CORR. FACTOR        0.90

SEA WATER INFORMATION
---------------------

INJECTION TEMP., F..      75.    SEA WATER VELO., FPS      9.00


INLET STEAM INFORMATION
-----------------------

AUX. STEAM, LB/HR...   11065.    MAIN STEAM, LB/HR...   418600.    TOTAL STEAM, LB/HR..   429665.
AUX. STEAM ENTHALPY     481.8    MAIN STEAM ENTHALPY      950.0    ADD'L. HEAT, BTU/HR    458000.
CHANGE, BTU/LB                   CHANGE, BTU/LB
SAT. TEMPERATURE, F     125.1    SAT. PRESSURE, PSIA     1.9646

BUNDLE INFORMATION
------------------

BUNDLE DIAMETER, FT      7.26    TUBE SHEET A., FT**2     41.38    WATERBOX DEPTH, FT..       3.63
VOLUME, FT**3.......    926.8    OVERALL LENGTH, FT..     22.06    TUBE PITCH/DIAM.....     1.6000
AREA RATIO..........    0.342

HEAT TRANSFER AND PUMPING INFORMATION
-------------------------------------

HEAT REJECTED..... 0.40350E 09    OVERALL U......  ...    657.21    LMTD, F.............      39.33
     BTU/HR                      BTU/(HR*FT**2*F)
S-W TEMP. RISE, F...    19.85    PINCH POINT, F .....     30.24    S-W FLOW RATE, CFS..     90.633
S-W FLOW RATE, GPM.. 40645.22    PUMPING POWER.......    68636.    S-W PRESSURE DROP...      12.19
                                      FT*LBF/SEC                        FT WATER
HEAT TRANSFER AREA,   16099.2    PUMPING POWER, HP...    125.16
FT**2
```

BUNDLE GEOMETRY INFORMATION

ROW NR.	RADIUS (IN.)	NR. OF TUBES
1	6.00	37.70
2	6.87	43.14
3	7.73	48.58
4	8.60	54.02
5	9.46	59.46
6	10.33	64.91
7	11.20	70.35
8	12.06	75.79
9	12.93	81.23
10	13.79	86.67
11	14.66	92.11
12	15.53	97.55
13	16.39	102.99
14	17.26	108.44
15	18.12	113.88
16	18.99	119.32
17	19.86	124.76
18	20.72	130.20
19	21.59	135.64
20	22.45	141.08
21	23.32	146.52
22	24.19	151.97
23	25.05	157.41
24	25.92	162.85
25	26.78	168.29
26	27.65	173.73
27	28.52	179.17
28	29.38	184.61
29	30.25	190.05
30	31.11	195.50
31	31.98	200.94
32	32.85	206.38
33	33.71	211.82
34	34.58	217.26
35	35.44	222.70
36	36.31	228.14
37	37.18	233.58
38	38.04	239.03
39	38.91	244.47
40	39.77	249.91
41	40.64	255.35
42	41.51	260.79
43	42.37	266.23
44	43.24	113.58

THE OUTER ROW HAS A PITCH OF 2.39 INCHES.

```
* * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                   *
*                   C O N M I N                     *
*               FORTRAN PROGRAM FOR                 *
*         CONSTRAINED FUNCTION MINIMIZATION         *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =    0.688359E 05

DECISION VARIABLES (X-VECTOR)
  1)     0.62500E 00  0.52700E 00  0.16000E 01  0.14800E 02  0.90000E 01

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.27000E 00 -0.55046E 00 -0.62584E 01 -0.27416E 00 -0.50475E 01 -0.13608E 00
  7)    -0.25705E 01 -0.72662E-02 -0.24230E 01 -0.49161E-01
```

```
FINAL OPTIMIZATION INFORMATION

 OBJ =    0.106307E 05

 DECISION VARIABLES (X-VECTOR)
   1)     0.73322E 00  0.68695E 00  0.16247E 01  0.12953E 02  0.35897E 01

 CONSTRAINT VALUES (G-VECTOR)
   1)    -0.11356E-01 -0.78775E 00 -0.88299E 01 -0.17013E-01 -0.50629E 01 -0.13387E 00
   7)    -0.29555E 01 -0.11132E-01 -0.24236E 01 -0.49014E-01

 THERE ARE     2 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     1    8

 THERE ARE     0 VIOLATED CONSTRAINTS

 THERE ARE     0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
      ABS(OBJ(I)-OBJ(I-1))    LESS THAN DABFUN FOR   3 ITERATIONS

 NUMBER OF ITERATIONS =    19

 OBJECTIVE FUNCTION WAS EVALUATED           140   TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED        140   TIMES
```

CVA (67) MAIN CONDENSER DESIGN

```
*********************************
*                               *
*  A N A L Y S I S   R E S U L T S  *
*                               *
*********************************
```

TUBE INFORMATION

TUBE OD, IN.........	0.7332	TUBE ID, IN.........	0.6869	TUBE WALL, IN.......	0.0231
TUBE LENGTH, FT.....	12.95	NR. OF TUBES.........	8860.6	MAT'L. CORR. FACTOR	0.99

SEA WATER INFORMATION

INJECTION TEMP., F..	75.	SEA WATER VELC., FPS	3.99

INLET STEAM INFORMATION

AUX. STEAM, LB/HR...	11065.	MAIN STEAM, LB/HR...	418600.	TOTAL STEAM, LB/HR..	429665.
AUX. STEAM ENTHALPY CHANGE, BTU/LB	981.8	MAIN STEAM ENTHALPY CHANGE, BTU/LB	950.0	ADD'L. HEAT, BTU/HR	458000.
SAT. TEMPERATURE, F	125.1	SAT. PRESSURE, PSIA	1.9646		

BUNDLE INFORMATION

BUNDLE DIAMETER, FT	9.83	TUBE SHEET A., FT**2	75.89	WATERBOX DEPTH, FT..	3.75
VOLUME, FT**3.......	1439.0	OVERALL LENGTH, FT..	20.45	TUBE PITCH/DIAM.....	1.6247
AREA RATIO..........	0.342				

HEAT TRANSFER AND PUMPING INFORMATION

HEAT REJECTED..... BTU/HR	0.40350E 09	OVERALL U...... ... BTU/(HR*FT**2*F)	465.10	LMTD, F.............	39.38
S-W TEMP. RISE, F...	19.78	PINCH POINT, F	30.31	S-W FLOW RATE, CFS..	90.987
S-W FLOW RATE, GPM..	40834.12	PUMPING POWER....... FT*LBF/SEC	10831.	S-W PRESSURE DROP... FT WATER	1.91
HEAT TRANSFER AREA, FT**2	22031.0	PUMPING POWER, HP...	19.69		

BUNCLE GEOMETRY INFCRMATICN

ROW NR.	RADIUS (IN.)	NR. OF TUBES
1	6.00	31.65
2	7.03	37.09
3	8.06	42.53
4	9.09	47.97
5	10.13	53.41
6	11.16	58.85
7	12.19	64.29
8	13.22	69.74
9	14.25	75.18
10	15.28	80.62
11	16.32	86.06
12	17.35	91.50
13	18.38	96.94
14	19.41	102.38
15	20.44	107.82
16	21.47	113.27
17	22.51	118.71
18	23.54	124.15
19	24.57	129.59
20	25.60	135.03
21	26.63	140.47
22	27.66	145.91
23	28.70	151.35
24	29.73	156.80
25	30.76	162.24
26	31.79	167.68
27	32.82	173.12
28	33.85	178.56
29	34.89	184.00
30	35.92	189.44
31	36.95	194.88
32	37.98	200.33
33	39.01	205.77
34	40.04	211.21
35	41.08	216.65
36	42.11	222.09
37	43.14	227.53
38	44.17	232.97
39	45.20	238.41
40	46.23	243.65
41	47.26	249.30
42	48.30	254.74
43	49.33	260.18
44	50.36	265.62
45	51.39	271.06
46	52.42	276.50
47	53.45	281.94
48	54.49	287.38
49	55.52	292.83
50	56.55	298.27
51	57.58	303.71
52	58.61	309.13

THE OUTER ROW HAS A PITCH OF 1.19 INCHES.

APPENDIX E

OPCODE1 PROGRAM LISTING

```
C      THIS SUBPROGRAM MAKES UP THE ANALYSIS PORTION OF OPCODE1, A
C      PROGRAM FOR THE OPTIMIZED DESIGN OF MARINE CONDENSERS BASED ON
C      THE APPLICATION OF THE COPES/CONMIN OPTIMIZATION PROGRAM TO THIS
C      ANALYSIS PROGRAM BASED ON THE HEI/DDS METHOD OF CALCULATING
C      CONDENSER PARAMETERS.  SEE'MARINE CONDENSER DESIGN USING
C      NUMERICAL OPTIMIZATION', A COMBINED ME AND MSME THESIS WRITTEN AT
C      THE NAVAL POSTGRADUATE SCHOOL, MONTEREY CALIFORNIA IN
C      DECEMBER, 1977, BY C.M. JOHNSON LT, USN.
       SUBROUTINE ANALIZ (ICALC)
       COMMON/GLOBCM/SDO,SDI,PITCH,ALGTH,VELC,SDC,XW,BNDIAM,
      1WBDPTH,VOL,POWER,FAC3,FAC2,CLOA,TUBES,ARATIC,HECOST,OBJ,QREJ,
      2WMS,WAS
       COMMON/BLOCK1/ROUGH,TID,VOIDID
       COMMON/BLOCK2/RADIUS(150),TUBRO(150)
       DATA IN,IOUT/5,6/
       DATA PI,TUPI,PIBY4,HFGAVG/3.14159,6.28319,0.785398,950./
       DIMENSION IDENT(20)
       GO TO (10,20,30),ICALC
 10    CONTINUE
C
C                ------------------------------------------------
C                           I N P U T   S E C T I O N
C                ------------------------------------------------
C
       F1=0.85
       VOIDID=12.0
       READ (IN,500) IDENT
       READ (IN,504) A
       READ (IN,502) SDO,SDI,XW,SDD,ALGTH,ROUGH,NPASS
       READ (IN,501) VELC,T1
       READ (IN,501) WMS,HFGMS,WAS,HFGAS,PSAT,TSAT,TRNSHT
       READ (IN,503) IDMATL
       IF (PSAT .GT. 0.0) GO TO 11
       PSAT=PSATFN(TSAT)
       GO TO 12
 11    TSAT=TSATFN(PSAT)
 12    CONTINUE
       IF (ABS(HFGMS) .LE. 1.0) HFGMS=HFGAVG
       IF (ABS(HFGAS) .LE. 1.0 .AND. WAS .GT. 1.0) HFGAS=HFGAVG
       WS=WMS+WAS
       CALL MATFAC (F2,IDMATL,XW)
       SPVOL=1./DENSE(TSAT)
       WRITE ( IOUT,600) IDENT
       WRITE ( IOUT,630)
       WRITE ( IOUT,631)
       WRITE ( IOUT,601)
       WRITE ( IOUT,602)  SDC,SDI,XW
       WRITE ( IOUT,608) ROUGH,ALGTH,F2
```

```
      WRITE (IOUT,609)  F1,NPASS,IDMATL                          OPC10490
      WRITE (IOUT,603)                                           OPC10500
      WRITE (IOUT,604)  T1,VELC                                  OPC10510
      WRITE (IOUT,605)                                           OPC10520
      WRITE (IOUT,606)  WAS,WMS,WS                               OPC10530
      WRITE (IOUT,607)  HFGAS,HFGMS,TRNSHT                       OPC10540
      WRITE (IOUT,625)  TSAT,PSAT                                OPC10550
      WRITE (IOUT,633)                                           OPC10560
      WRITE (IOUT,634)                                           OPC10570
      WRITE (IOUT,635)  A                                        OPC10580
      RETURN                                                     OPC10590
   20 CONTINUE                                                   OPC10600
C                                                                OPC10610
C           ------------------------------------------           OPC10620
C                A N A L Y S I S   S E C T I O N                 OPC10630
C           ------------------------------------------           OPC10640
C                                                                OPC10650
      TOD=SDO/12.                                                OPC10660
      TID=SDI/12.                                                OPC10670
      PITCH=SDD*SDO                                              OPC10680
      XW=(SDO-SDI)/2.0                                           OPC10690
      WS=WMS+WAS                                                 OPC10700
      S=PI*TOD                                                   OPC10710
      G1=PIBY4*TID**2*448.46                                     OPC10720
      F=S/G1                                                     OPC10730
      U=270.*SQRT(VELC)                                          OPC10740
      CALL MATFAC (F2,IDMATL,XW)                                 OPC10750
      F3=TEMFAC(T1)                                              OPC10760
      UC=F1*F2*F3*U                                              OPC10770
      FAC1=(UC*ALGTH*F)/(500.*VELC)                              OPC10780
      TOUT=TSAT+((T1-TSAT)/EXP(FAC1))                            OPC10790
      FAC2=TOUT-T1                                               OPC10800
      FAC3=TSAT-TOUT                                             OPC10810
      FAC4=TSAT-T1                                               OPC10820
      TAVG=(T1+TOUT)/2.0                                         OPC10830
      ALMTD=FAC2/(ALOG(FAC4/FAC3))                               OPC10840
      QIN=WAS*HFGAS+WMS*HFGMS+TRNSHT                             OPC10850
      G=QIN/(500.0*FAC2)                                         OPC10860
      CFS=G/448.46                                               OPC10870
      HTAREA=(ALGTH*G*F)/VELC                                    OPC10880
      TUBES=G/(G1*VELC)                                          OPC10890
      QREJ=UC*HTAREA*ALMTD                                       OPC10900
      AHOLES=PIBY4*TOD**2*TUBES                                  OPC10910
      CALL GEOM (NROWS,PSPACE,IFLAG)                             OPC10920
      IF (IFLAG .EQ. 1) NROWS=NROWS+1                            OPC10930
      BNDRAD=RADIUS(NROWS)/12.+0.5*TOD                           OPC10940
      BNDIAM=2.*BNDRAD                                           OPC10950
      WEDPTH=BNDRAD                                              OPC10960
```

```
      IF (WBDPTH .GT. 3.75) WBDPTH=3.75
      CLCA=ALGTH+(WBDPTH*2.0)
      TSAREA=PIBY4*BNDIAM**2
      ARATIO=AHOLES/TSAREA
      WSPM=WS/60.
      HWVOL=SPVOL*WSPM
      CALL FRIFAC (FF)
      CALL PRSDRP (TSAREA,TUBES,TID,NPASS,VELC,ENDK,WBIN,WBCUT)
      TUBLOS=FF*(ALGTH/TID)*VELC**2/64.4
      ENDLOS=ENDK*VELC**2/64.4
      WBLOS=WBIN+WBOUT
      DELP=TUBLOS+ENDLOS+WBLOS
      PCWER=TUBES*DELP*PIBY4*TID**2*VELC*DENSE(TAVG)
      HF=POWER/55C.
      WBVOL=2.0*(PI/6.0)*WBDPTH*(WBDPTH**2+3.0*BNDRAD**2)
      BNDVOL=PIBY4*BNDIAM**2*ALGTH
      VCL=WBVCL+BNDVOL+HWVOL
C
C     ***********************************************************************
C     SET OBJ= TO WHATEVER IS BEING USED AS AN OBJECTIVE FUNCTION.
C     REMEMBER TO INCLUDE A WEIGHTING FACTOR, A, IF AN EQUALITY
C     CONSTRAINT IS BEING MET.  SEE CHAPTER TWO OF REFERENCE.
C     ***********************************************************************
C
      OBJ=VOL+A*PCWER
      RETURN
   30 CONTINUE
C
C               ------------------------------------------------
C                          O U T P U T   S E C T I O N
C               ------------------------------------------------
C
      WRITE (IOUT,600) IDENT
      WRITE (IOUT,630)
      WRITE (IOUT,632)
      WRITE (IOUT,601)
      WRITE (IOUT,602) SDO,SDI,XW
      WRITE (IOUT,624) ALGTH,TUBES,F2
      WRITE (IOUT,603)
      WRITE (IOUT,604) T1,VELC
      WRITE (IOUT,605)
      WRITE (IOUT,606) WAS,WMS,WS
      WRITE (IOUT,607) HFGAS,HFGMS,TRNSHT
      WRITE (IOUT,625) TSAT,PSAT
      WRITE (IOUT,611)
      WRITE (IOUT,614) BNDIAM,TSAREA,WBDPTH
      WRITE (IOUT,615) VCL,CLOA,SDD,ARATIO
      WRITE (IOUT,616)
```

```
      WRITE (IOUT,617) CREJ,UC,ALMTD
      WRITE (IOUT,618)
      WRITE (IOUT,619) FAC2,FAC3,CFS
      WRITE (IOUT,621) G,POWER,DELP
      WRITE (IOUT,622)
      WRITE (IOUT,623) HTAREA,HP
      WRITE (IOUT,620)
      DC 101 I=1,NROWS
      WRITE (IOUT,612) I,RADIUS(I),TUBRC(I)
101   CONTINUE
      IF (IFLAG .EQ. 0) GO TO 102
      WRITE (IOUT,613) PSPACE
102   CCNTINUE
      RETURN
500   FORMAT(20A4)
501   FCRMAT(8F10.0)
502   FCRMAT(5F10.4,F10.7,I2)
503   FORMAT(8I10)
504   FCRMAT(6E12.5)
600   FCRMAT(1H1,////,T5,20A4,/)
601   FCRMAT(1H0,//,T5,16HTUBE INFORMATICN,/,T5,16H----------------,/)
602   FCRMAT(1H ,T5,20HTUBE OD, IN.........,F10.4,T40,20HTUBE ID, IN....
     1.....,F10.4,T75,20HTUBE WALL, IN.......,F10.4)
603   FCRMAT(1H0,//,T5,21HSEA WATER INFCRMATION,/,T5,21H----------------
     1-----,/)
604   FCRMAT(1H ,T5,20HINJECTION TEMP., F..,F10.0,T40,20HSEA WATER VELC.
     1, FPS,F10.2,/)
605   FCRMAT(1H0,//,T5,23HINLET STEAM INFORMATICN,/,T5,23H--------------
     1---------,/)
606   FCRMAT(1H ,T5,20HAUX. STEAM, LB/HR...,F10.0,T40,20HMAIN STEAM, LB/
     1HR...,F10.0,T75,20HTOTAL STEAM, LB/HR..,F10.0)
607   FCRMAT(1H ,T5,20HAUX. STEAM ENTHALPY ,F10.1,T40,20HMAIN STEAM ENTH
     1ALPY ,F10.1,T75,20HADD'L. HEAT, BTU/HR ,F10.0,/T5,14HCHANGE, BTU/L
     2B,T40,14HCHANGE, BTU/LB)
608   FCRMAT(1H ,T5,20HABS. ROUGHNESS, FT..,F10.7,T40,20HTUBE LENGTH, FT
     1.....,F10.4,T75,20HMAT'L. CORR. FACTOR ,F10.2)
609   FORMAT(1H ,T5,20HTUBE CLEAN. FACTCR..,F10.2,T40,20HNR. CF PASSES..
     1......,I10,T75,20HMATERIAL IDENT......,I10)
610   FORMAT(1H0,130H***********************************************************
     1**************************************************************
     2*************)
611   FCRMAT(1H0,T5,18HBUNDLE INFCRMATICN,/,T5,18H------------------,/)
612   FCRMAT(1H ,T5,I3,T22,F6.2,T38,F6.2)
613   FCRMAT(1H0,T5,29HTHE CUTER ROW HAS A PITCH CF ,F6.2,8H INCHES.)
614   FCRMAT(1H ,T5,20HBUNDLE DIAMETER, FT ,F10.2,T40,20HTUBE SHEET A.,
     1FT**2,F10.2,T75,20HWATERBOX DEPTH, FT..,F10.2)
615   FCRMAT(1H ,T5,20HVOLUME, FT**3.......,F10.1,T40,20HCVERALL LENGTH,
     1 FT..,F10.2,T75,20HTUBE PITCH/DIAM.....,F10.4,/,T5,
```

```
      22CHAREA RATIO...........,F10.3)                                  OPC11930
  616 FORMAT(1H0,//,T5,37HHEAT TRANSFER AND PUMPING INFORMATION,/,T5,37HOPC11940
     1-------------------------------------,/)                          OPC11950
  617 FORMAT(1H ,T5,18HHEAT REJECTED......,E12.5,T40,20HOVERALL U......  OPC11960
     1...,F10.2,T75,20HLMTD, F..............,F10.2)                      OPC11970
  618 FORMAT(1H ,T10,6HBTU/HR,T40,16HBTU/(HR*FT**2*F))                  OPC11980
  619 FORMAT(1H ,T5,20HS-W TEMP. RISE, F...,F10.2,T40,20HPINCH POINT, F OPC11990
     1.....,F10.2,T75,20HS-W FLOW RATE, CFS..,F10.3)                     OPC12000
  620 FORMAT(1H1,T5,27HBUNDLE GEOMETRY INFORMATION,/,                   OPC12010
     1T5,27H---------------------------,//,                              OPC12020
     2T5,7HROW NR.,T20,12HRADIUS (IN.),T35,12HNR. OF TUBES,/)           OPC12030
  621 FORMAT(1H ,T5,20HS-W FLOW RATE, GPM..,F10.2,T40,20HPUMPING POWER..OPC12040
     1.....,F10.0,T75,20HS-W PRESSURE DROP...,F10.2)                     OPC12050
  622 FORMAT(1H ,T45,10HFT*LBF/SEC,T80,8HFT WATER)                       OPC12060
  623 FORMAT(1H ,T5,20HHEAT TRANSFER AREA, ,F10.1,T40,20HPUMPING POWER, OPC12070
     1HP...,F10.2,/,T5,5HFT**2)                                          OPC12080
  624 FORMAT(1H ,T5,20HTUBE LENGTH, FT.....,F10.2,T40,20HNR. OF TUBES...OPC12090
     1.....,F10.1,T75,20HMAT'L. CORR. FACTOR ,F10.2)                     OPC12100
  625 FORMAT(1H ,T5,20HSAT. TEMPERATURE, F ,F10.1,T40,20HSAT. PRESSURE, OPC12110
     1PSIA ,F10.4,//)                                                    OPC12120
  630 FORMAT(1H0,T45,34H**********************************,/            OPC12130
     1          ,T45,34H*                                *)              OPC12140
  631 FORMAT(1H ,T45,34H*      I N P U T   V A L U E S   *,/            OPC12150
     1          ,T45,34H*                                *,/             OPC12160
     2          ,T45,34H**********************************)              OPC12170
  632 FORMAT(1H ,T45,34H* A N A L Y S I S   R E S U L T S *,/,          OPC12180
     1           T45,34H*                                *,/,            OPC12190
     2           T45,34H**********************************)              OPC12200
  633 FORMAT(1H ,//,T50,20H TUBE MATERIAL CODE ,/,T50,20H ---------------OPC12210
     1---- ,//,                                                          OPC12220
     2T50,20HADMIRALTY METAL... 1,/,                                     OPC12230
     3T50,20HARSENICAL COPPER.. 1,/,                                     OPC12240
     4T50,20HALUMINUM.......... 1,/,                                     OPC12250
     5T50,20HALUMINUM BRASS.... 2,/,                                     OPC12260
     6T50,20HALUMINUM BRONZE... 2,/,                                     OPC12270
     7T50,20HMUNTZ METAL....... 2,/,                                     OPC12280
     8T50,20H90-10 CU-NI....... 3,/,                                     OPC12290
     9T50,20H70-30 CU-NI....... 4)                                       OPC12300
  634 FORMAT(1H ,T50,11HCOLD ROLLED,/,                                   OPC12310
     1T50,20HLOW CARBON STEEL.. 5,/,                                     OPC12320
     2T50,16HSTAINLESS STEELS,/,                                         OPC12330
     3T52,18HTYPE 410/430.... 6,/,                                       OPC12340
     4T52,18HTYPE 304/316.... 7,/,                                       OPC12350
     5T52,18HTYPE 329........ 8,/,                                       OPC12360
     6T50,20HTITANIUM.......... 9)                                       OPC12370
  635 FORMAT(1H ,//,T5,37HOBJECTIVE FUNCTION WEIGHTING FACTOR  ,G11.4)  OPC12380
      END                                                                OPC12390
      SUBROUTINE FRIFAC(FF)                                              OPC12400
```

```
      COMMON/GLOBCM/SDO,SDI,PITCH,ALGTH,VELC,SDC,XW,ENDIAM,              OPC12410
     1WBCPTH,VOL,POWER,FAC3,FAC2,CLOA,TUBES,ARATIC,HECOST,CBJ,QREJ,      OPC12420
     2WMS,WAS                                                            OPC12430
      COMMON/BLOCK1/ROUGH,TID,VOIDID                                     OPC12440
      DATA IN,IOUT/5,6/                                                  OPC12450
C                                                                        OPC12460
C.....THIS SUBROUTINE SOLVES THE TRANSCENTENTIAL EQUATION FOR THE        OPC12470
C.....FRICTION FACTOR INSIDE A TUBE.                                     OPC12480
C                                                                        OPC12490
C                                                                        OPC12500
      FF=0.01                                                            OPC12510
      IER=0                                                              OPC12520
      A=ROUGH/(3.7*TID)                                                  OPC12530
      B=2.608E-5/(VELC*TID)                                              OPC12540
      DO 10 I=1,9999                                                     OPC12550
      TEST=1./SQRT(FF)+2.*ALOG10(A+B/SQRT(FF))                           OPC12560
      IF (ABS (TEST) .LT. 1.0E-3) GO TO 20                               OPC12570
      IER=IER+1                                                          OPC12580
      IF (IER .EQ. 9999) GO TO 30                                        OPC12590
      FF=FF+0.00001                                                      OPC12600
   10 CONTINUE                                                           OPC12610
   20 RETURN                                                             OPC12620
   30 WRITE (IOUT,600)                                                   OPC12630
      RETURN                                                             OPC12640
  600 FORMAT(1H0,20X,32HNO SOLUTION FOR FRICTION FACTOR.)                OPC12650
      END                                                                OPC12660
      SUBROUTINE GEOM (NROWS,PSPACE,IFLAG)                               OPC12670
      COMMON/GLOBCM/SDO,SDI,PITCH,ALGTH,VELC,SDC,XW,ENDIAM,              OPC12680
     1WBCPTH,VOL,POWER,FAC3,FAC2,CLOA,TUBES,ARATIC,HECOST,CBJ,QREJ,      OPC12690
     2WMS,WAS                                                            OPC12700
      COMMON/BLOCK1/ROUGH,TID,VOIDID                                     OPC12710
      COMMON/BLOCK2/RADIUS(150),TUBRO(150)                               OPC12720
      DATA PI,TUPI,PIBY4,HFGAVG/3.14159,6.28319,0.785398,950./           OPC12730
C                                                                        OPC12740
C.....THE DIMENSION 'QSPACE' IS THE DISTANCE, CENTER TO CENTER, BETWEEN OPC12750
C.....CONCENTRIC ROWS.  IT IS COMPUTED FOR TUBE SPACING ON A 60 DEGREE   OPC12760
C.....TRIANGULAR PATTERN.                                                OPC12770
C                                                                        OPC12780
      QSPACE=PITCH*0.866                                                 OPC12790
C                                                                        OPC12800
C.....CALCULATE CIRCUM. AND NR. OF TUBES IN FIRST (INNERMOST) ROW.       OPC12810
C                                                                        OPC12820
      IFLAG=0                                                            OPC12830
      CIRC=PI*VOIDID                                                     OPC12840
      RADIUS(1)=VOIDID/2.                                                OPC12850
      TUBRO(1)=CIRC/PITCH                                                OPC12860
      SUMTUB=TUBRO(1)                                                    OPC12870
      NROWS=1                                                            OPC12880
```

```
      REMAIN=TUBES-SUMTUB
C
C.....TEST TO SEE IF WITHIN 0.1 PERCENT OF THE REQ'D. TUBES HAVE BEEN
C.....ACCOUNTED FOR.
C
      IF (ABS(REMAIN) .LE. (0.001*TUBES)) GO TO 300
C
C.....THE 100 LOOP FILLS CONCENTRIC ROWS, TESTING FOR INSERTING MORE
C.....TUBES THAN ARE AVAILIBLE.
C
      DO 100 I=2,100
      II=I
      RADIUS(I)=RADIUS(1)+FLOAT(NROWS)*CSPACE
      CIRC=TUPI*RADIUS(I)
      TUBRO(I)=CIRC/PITCH
      SUMTUB=SUMTUB+TUBRO(I)
      REMAIN=TUBES-SUMTUB
      IF (REMAIN) 200,300,101
101   NROWS=NROWS+1
100   CONTINUE
200   IFLAG=1
      PART=TUBES-(SUMTUB-TUBRO(II))
      ASPACE=(CIRC-(PART*SDO))/PART
      PSPACE=ASPACE+SDO
      TUBRO(II)=PART
300   RETURN
      END
      SUBROUTINE MATFAC(F2,KEY,XW)
      IMPLICIT REAL (M)
      DIMENSION THICK(7),MATL1(7),MATL2(7),MATL3(7),MATL4(7),MATL5(7)
     1,MATL6(7),MATL7(7),MATL8(7),MATL9(5),THICK9(5),X(1),Y(1)
      DATA THICK/0.022,.028,.035,.049,.065,.083,.109/
      DATA MATL1/1.06,1.04,1.02,1.00,.96,.92,.87/
      DATA MATL2/1.03,1.02,1.00,.97,.94,.90,.84/
      DATA MATL3/.99,.97,.94,.90,.85,.80,.74/
      DATA MATL4/0.93,.90,.87,.82,.77,.71,.64/
      DATA MATL5/1.00,.98,.95,.91,.86,.80,.74/
      DATA MATL6/.88,.85,.82,.76,.70,.65,.59/
      DATA MATL7/.83,.79,.75,.69,.63,.56,.49/
      DATA MATL8/.78,.76,.74,.69,.65,.60,.54/
      DATA THICK9/.012,.022,.028,.035,.049/
      DATA MATL9/.95,.85,.81,.77,.71/
      X(1)=XW
      GO TO (1,2,3,4,5,6,7,8,9),KEY
1     CALL INTRPL (7,THICK,MATL1,1,X,Y)
      GO TO 20
2     CALL INTRPL (7,THICK,MATL2,1,X,Y)
      GO TO 20
```

```
3     CALL INTRPL (7,THICK,MATL3,1,X,Y)                              OPC13370
      GO TO 20                                                       OPC13380
4     CALL INTRPL (7,THICK,MATL4,1,X,Y)                              OPC13390
      GO TO 20                                                       OPC13400
5     CALL INTRPL (7,THICK,MATL5,1,X,Y)                              OPC13410
      GO TO 20                                                       OPC13420
6     CALL INTRPL (7,THICK,MATL6,1,X,Y)                              OPC13430
      GO TO 20                                                       OPC13440
7     CALL INTRPL (7,THICK,MATL7,1,X,Y)                              OPC13450
      GO TO 20                                                       OPC13460
8     CALL INTRPL (7,THICK,MATL8,1,X,Y)                              OPC13470
      GO TO 20                                                       OPC13480
9     CALL INTRPL (5,THICK9,MATL9,1,X,Y)                             OPC13490
20    F2=Y(1)                                                        OPC13500
      RETURN                                                         OPC13510
      END                                                            OPC13520
      SUBROUTINE PRSDRP (TSAREA,TUBES,TID,NPASS,VELC,ENDK,WBIN,WBOUT) OPC13530
      DIMENSION VEL1(6),DELP1(6),DELP2(6),DELP3(6),XX(1),YY(1)       OPC13540
      DATA PI,TUPI,PIBY4,HFGAVG/3.14159,6.28319,0.785398,950./       OPC13550
      DATA VEL1 /2.0,4.0,6.0,8.0,10.0,12.0/                          OPC13560
      DATA DELP1/0.06,0.24,0.56,1.0,1.54,2.13/                       OPC13570
      DATA DELP2/0.01,0.07,0.16,0.29,0.46,0.66/                      OPC13580
      DATA DELP3/0.03,0.12,0.28,0.5,0.77,1.13/                       OPC13590
      BAREA=TSAREA/TUBES                                             OPC13600
      SAREA=PIBY4*TID**2                                             OPC13610
      BETA=SAREA/BAREA                                               OPC13620
      ENLOSS=0.5*(1.0-BETA**2)                                       OPC13630
      EXLOSS=(1.0-BETA**2)**2                                        OPC13640
      ENDK=FLOAT(NPASS)*(ENLOSS+EXLOSS)                              OPC13650
      WBVEL=0.75*VELC                                                OPC13660
      GO TO (10,20),NPASS                                            OPC13670
10    XX(1)=WBVEL                                                    OPC13680
      CALL INTRPL (6,VEL1,DELP1,1,XX,YY)                             OPC13690
      WBIN=YY(1)                                                     OPC13700
      CALL INTRPL (6,VEL1,DELP2,1,XX,YY)                             OPC13710
      WBOUT=YY(1)                                                    OPC13720
      GO TO 30                                                       OPC13730
20    XX(1)=WBVEL                                                    OPC13740
      CALL INTRPL (6,VEL1,DELP1,1,XX,YY)                             OPC13750
      WBIN=YY(1)                                                     OPC13760
      CALL INTRPL (6,VEL1,DELP3,1,XX,YY)                             OPC13770
      WBOUT=YY(1)                                                    OPC13780
30    RETURN                                                         OPC13790
      END                                                            OPC13800
      FUNCTION DENSE (X)                                             OPC13810
C                                                                    OPC13820
C.....DENSITY AS A FUNCTION OF SATURATION TEMPERATURE.                OPC13830
C                                                                    OPC13840
```

```
      DENSE=63.8-.01781*X+1.132E-05*X**2-6.786E-08*X**3                 OPC13850
      RETURN                                                            OPC13860
      END                                                               OPC13870
      FUNCTION PSATFN(T)                                                OPC13880
      R=T+460.                                                          OPC13890
      PSATFN=EXP(14.150119-(6452.562/R)-(837533.21/R**2))               OPC13900
      RETURN                                                            OPC13910
      END                                                               OPC13920
      FUNCTION TEMFAC(X)                                                OPC13930
      DIMENSION TEMP(8),FACTOR(8),XX(1),YY(1)                           OPC13940
      DATA TEMP/30.,40.,50.,60.,70.,80.,90.,100./                       OPC13950
      DATA FACTOR/0.65,0.75,0.85,0.93,1.0,1.05,1.08,1.1/                OPC13960
      XX(1)=X                                                           OPC13970
      CALL INTRPL(8,TEMP,FACTOR,1,XX,YY)                                OPC13980
      TEMFAC=YY(1)                                                      OPC13990
      RETURN                                                            OPC14000
      END                                                               OPC14010
      FUNCTION TSATFN(P)                                                OPC14020
      DATA IN,IOUT/5,6/                                                 OPC14030
      AA=(ALOG(P)-14.150119)                                            OPC14040
      DET=6452.5621**2-(4.0*AA*837533.21)                               OPC14050
      IF (DET) 10,20,20                                                 OPC14060
   10 WRITE (IOUT,600)                                                  OPC14070
      RETURN                                                            OPC14080
   20 X=(-6452.5621+SQRT(DET))/(2.0*AA)                                 OPC14090
      Y=(-6452.5621-SQRT(DET))/(2.0*AA)                                 OPC14100
      IF (X-Y) 30,40,40                                                 OPC14110
   30 Y=Y-460.                                                          OPC14120
      TSATFN=Y                                                          OPC14130
      RETURN                                                            OPC14140
   40 X=X-460.                                                          OPC14150
      TSATFN=X                                                          OPC14160
      RETURN                                                            OPC14170
  600 FORMAT(1H0,//,20X,37HSUBROUTINE TSATFN FINDS COMPLEX ROOTS)       OPC14180
      END                                                               OPC14190
      BLOCK DATA                                                        OPC14200
      COMMON/GLOBCM/DUMMY4(1500)                                        OPC14210
      DATA DUMMY4/1500*0.0/                                             OPC14220
      END                                                               OPC14230
C.......................................................................INTR0010
C                                                                       INTR0020
C    SUBROUTINE INTRPL          (CATEGORY E2)                           INTR0030
C                                                                       INTR0040
C    1. IDENTIFICATION:                                                 INTR0050
C                                                                       INTR0060
C       A. NAME: INTERPOLATION OF A SINGLE VALUED FUNCTION              INTR0070
C                BASED ON LOCAL PROCEDURES                              INTR0080
C                                                                       INTR0090
```

```
C        B. PROGRAMMER:  HIROSHI AKIMA
C
C        C. IMPLEMENTER: MICHAEL CORCORAN
C
C        D. DATE: MARCH, 1973
C
C     2. PURPOSE:
C
C        A. THE INTRPL SUBROUTINE INTERPOLATES, FROM VALUES OF THE
C           FUNCTION GIVEN AS ORDINATES OF INPUT DATA POINTS IN AN
C           X-Y PLANE AND FOR A GIVEN SET OF X VALUES (ABSCISSAS OF
C           DESIRED POINTS), THE VALUES OF A SINGLE VALUED FUNCTION
C           Y = Y(X).
C
C     3. USAGE:
C
C        A. CALLING STATEMENT:
C
C           CALL INTRPL(L,X,Y,N,U,V)
C
C           WHERE THE INPUT PARAMETERS ARE:
C
C           1) L  -  THE NUMBER OF INPUT DATA POINTS (MUST BE 2 OR MORE)
C
C           2) X  -  AN ARRAY OF DIMENSION L STORING THE X VALUES
C                    (ABSCISSAS) OF THE INPUT DATA POINTS IN ASCENDING
C                    ORDER....X(I+1) > X(I)     (TYPE REAL*4)
C
C           3) Y  -  AN ARRAY OF DIMENSION L STORING THE Y VALUES
C              (ORDINATES) OF THE INPUT DATA POINTS    (TYPE REAL*4)
C
C           4) N  -  THE NUMBER OF POINTS AT WHICH INTERPOLATION OF THE
C                    Y VALUE (ORDINATE) IS DESIRED  (MUST BE ONE OR MORE)
C
C           5) U  -  THE ARRAY OF DIMENSION N STORING THE X VALUES
C                    (ABSCISSAS) OF DESIRED POINTS    (TYPE REAL*4)
C
C
C           AND WHERE THE OUTPUT PARAMETER IS
C
C           6) V  -  THE ARRAY OF DIMENSION N WHERE THE INTERPOLATED
C                    Y VALUES (ORDINATES) ARE TO BE PLACED
C
C        B. ERROR MESSAGES:
C
C           1)  "***    L = 1 OR LESS.
C                    L =(I7)            N =(I7)
C               ERROR DETECTED IN ROUTINE     INTRPL"  (THE APPROPRIATE
```

```
C           VALUES ARE PRINTED WHERE FORMATS ARE INDICATED)
C
C       2)  "***    N = 0 OR LESS.
C               L =(I7)                N =(I7)
C           ERROR DETECTED IN ROUTINE      INTRPL"
C
C       3)  "***    IDENTICAL X VALUES.
C               I =(I7)                X(I) =(E12.3)
C               L =(I7)                N =(I7)
C           ERROR DETECTED IN ROUTINE      INTRPL"    ( THE VALUES IN
C           THE X ARRAY MUST BE IN STRICT ASCENDING SEQUENCE.)
C
C       4)  "***    X VALUES OUT OF SEQUENCE.
C               I =(I7)                X(I) =(E12.3)
C               L =(I7)                I =(I7)
C           ERROR DETECTED IN ROUTINE      INTRPL"  ( X(I) < X(I-1) FOR
C                                                    SOME I BETWEEN
C                                                    2 AND L. )
C
C   4. MODE OF ARITHMETIC:
C
C      SINGLE PRECISION
C
C   5. REMARKS:
C
C      A. WHEN THE FUNCTION TO BE INTERPOLATED REPRESENTS A PERIODIC
C         FUNCTION AND A SET OF L DATA POINTS COVERS A WHOLE PERIOD,
C         TWO ADDITIONAL DATA POINTS SHOULD BE ADDED AT EACH END AND
C         A SET OF L+4 DATA POINTS SHOULD BE GIVEN AS THE INPUT DATA
C         POINTS TO THIS SUBROUTINE.
C
C      B. CORE REQUIREMENT FOR INTRPL:  2968 BYTES.
C
C      C. NO SUBROUTINES OR FUNCTION SUBPROGRAMS ARE REQUIRED.
C
C      D. FOR THE CONVENIENCE OF THE NPS USER, THE ORIGINAL FORTRAN
C         PROGRAM WAS MODIFIED SLIGHTLY. AN UNNECESSARY INPUT
C         PARAMETER - IU, WHICH DESIGNATED THE OUPUT DEVICE NUMBER
C         FOR ERROR MESSAGES FROM INTRPL, WAS ELIMINATED FROM THE
C         PARAMETER LIST, AND THE FORTRAN CODE WAS MODIFIED TO CHANNEL
C         ALL ERROR MESSAGES TO THE LINE PRINTER AUTOMATICALLY.
C
C   6. METHOD:
C
C         THIS ROUTINE IS DEVISED IN SUCH A WAY THAT A CURVE DRAWN
C         THROUGH BOTH THE GIVEN AND INTERPOLATED POINTS WILL APPEAR
C         SMOOTH AND NATURAL, FREE OF UNNATURAL WIGGLES.  IT IS BASED
C         ON A PIECEWISE FUNCTION COMPOSED OF A SET OF POLYNOMIALS,
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```
C           EACH OF DEGREE THREE, AT MOST, AND APPLICABLE TO SUCCESSIVE
C           INTERVALS OF THE GIVEN POINTS.  IN THIS METHOD, THE SLOPE OF
C           THE CURVE IS DETERMINED AT EACH GIVEN POINT LOCALLY, AND
C           EACH POLYNOMIAL REPRESENTING A PORTION OF THE CURVE BETWEEN
C           A PAIR OF GIVEN POINTS IS DETERMINED BY THE COORDINATES OF
C           AND THE SLOPES AT THE POINTS.  COMPARISON INDICATES THAT THE
C           CURVE OBTAINED BY THIS METHOD IS CLOSER TO A MANUALLY DRAWN
C           CURVE THAN THOSE DRAWN BY OTHER MATHEMATICAL METHODS...
C
C           A DETAILED EXPLANATION OF THE METHOD CAN BE FOUND IN THE
C           OCTOBER 1970 ISSUE, JOURNAL OF THE ACM, PAGE 589, ENTITLED:
C           "A NEW METHOD OF INTERPOLATION AND SMOOTH CURVE FITTING
C            BASED ON LOCAL PROCEDURES", BY HIROSHI AKIMA.
C
C
C           A DESCRIPTION OF THE ALGORITHM USED PLUS THE ORIGINAL
C           FORTRAN PROGRAM IS GIVEN IN THE OCTOBER 1972 ISSUE,
C           COMMUNICATIONS OF THE ACM, PAGE 914, ENTITLED:
C           "INTERPOLATION AND SMOOTH CURVE FITTING BASED ON LOCAL
C            PROCEDURES", BY HIROSHI AKIMA.
C
C
C.....................................................................
C
C
      SUBROUTINE  INTRPL(L,X,Y,N,U,V)
C INTERPOLATION OF A SINGLE-VALUED FUNCTION
C THIS SUBROUTINE INTERPOLATES, FROM VALUES OF THE FUNCTION
C GIVEN AS ORDINATES OF INPUT DATA POINTS IN AN X-Y PLANE
C AND FOR A GIVEN SET OF X VALUES (ABSCISSAS), THE VALUES OF
C A SINGLE-VALUED FUNCTION Y = Y(X).
C THE INPUT PARAMETERS ARE
C       L  = NUMBER OF INPUT DATA POINTS
C            (MUST BE 2 OR GREATER)
C       X  = ARRAY OF DIMENSION L STORING THE X VALUES
C            (ABSCISSAS) OF INPUT DATA POINTS
C            (IN ASCENDING ORDER)
C       Y  = ARRAY OF DIMENSION L STORING THE Y VALUES
C            (ORDINATES) OF INPUT DATA POINTS
C       N  = NUMBER OF POINTS AT WHICH INTERPOLATION OF THE
C            Y VALUE (ORDINATE) IS DESIRED
C            (MUST BE 1 OR GREATER)
C       U  = ARRAY OF DIMENSION N STORING THE X VALUES
C            (ABSCISSAS) OF DESIRED POINTS
C THE OUTPUT PARAMETER IS
C       V  = ARRAY OF DIMENSION N WHERE THE INTERPOLATED Y
C            VALUES (ORDINATES) ARE TO BE DISPLAYED
C DECLARATION STATEMENTS
```

```
      DIMENSION      X(L),Y(L),U(N),V(N)                                INTR1540
      EQUIVALENCE    (PO,X3),(QO,Y3),(Q1,T3)                            INTR1550
      REAL           M1,M2,M3,M4,M5                                     INTR1560
      EQUIVALENCE    (UK,DX),(IMN,X2,A1,M1),(IMX,X5,A5,M5),             INTR1570
     1               (J,SW,SA),(Y2,W2,W4,C2),(Y5,W3,C3)                 INTR1580
C PRELIMINARY PROCESSING                                                INTR1590
   10 LO=L                                                              INTR1600
      LM1=LO-1                                                          INTR1610
      LM2=LM1-1                                                         INTR1620
      LP1=LO+1                                                          INTR1630
      NO=N                                                              INTR1640
      IF(LM2.LT.0)          GO TO 90                                    INTR1650
      IF(NO.LE.0)           GO TO 91                                    INTR1660
      DO 11  I=2,LO                                                     INTR1670
        IF(X(I-1)-X(I))     11,95,96                                    INTR1680
   11   CONTINUE                                                        INTR1690
      IPV=0                                                             INTR1700
C MAIN DO-LOOP                                                          INTR1710
      DO 80  K=1,NO                                                     INTR1720
        UK=U(K)                                                         INTR1730
C ROUTINE TO LOCATE THE DESIRED POINT                                   INTR1740
   20   IF(LM2.EQ.0)        GO TO 27                                    INTR1750
        IF(UK.GE.X(LO))     GO TO 26                                    INTR1760
        IF(UK.LT.X(1))      GO TO 25                                    INTR1770
        IMN=2                                                           INTR1780
        IMX=LO                                                          INTR1790
   21   I=(IMN+IMX)/2                                                   INTR1800
        IF(UK.GE.X(I))      GO TO 23                                    INTR1810
   22   IMX=I                                                           INTR1820
        GO TO 24                                                        INTR1830
   23   IMN=I+1                                                         INTR1840
   24   IF(IMX.GT.IMN)      GO TO 21                                    INTR1850
        I=IMX                                                           INTR1860
        GO TO 30                                                        INTR1870
   25   I=1                                                             INTR1880
        GO TO 30                                                        INTR1890
   26   I=LP1                                                           INTR1900
        GO TO 30                                                        INTR1910
   27   I=2                                                             INTR1920
C CHECK IF I = IPV                                                      INTR1930
   30   IF(I.EQ.IPV)        GO TO 70                                    INTR1940
        IPV=I                                                           INTR1950
C ROUTINES TO PICK UP NECESSARY X AND Y VALUES AND                      INTR1960
C          TO ESTIMATE THEM IF NECESSARY                                INTR1970
   40   J=I                                                             INTR1980
        IF(J.EQ.1)          J=2                                         INTR1990
        IF(J.EQ.LP1)        J=LO                                        INTR2000
        X3=X(J-1)                                                       INTR2010
```

```
      Y3=Y(J-1)                                                         INTR2020
      X4=X(J)                                                           INTR2030
      Y4=Y(J)                                                           INTR2040
      A3=X4-X3                                                          INTR2050
      M3=(Y4-Y3)/A3                                                     INTR2060
      IF(LM2.EQ.0)          GO TO 43                                    INTR2070
      IF(J.EQ.2)            GO TO 41                                    INTR2080
      X2=X(J-2)                                                         INTR2090
      Y2=Y(J-2)                                                         INTR2100
      A2=X3-X2                                                          INTR2110
      M2=(Y3-Y2)/A2                                                     INTR2120
      IF(J.EQ.LC)           GO TO 42                                    INTR2130
   41 X5=X(J+1)                                                         INTR2140
      Y5=Y(J+1)                                                         INTR2150
      A4=X5-X4                                                          INTR2160
      M4=(Y5-Y4)/A4                                                     INTR2170
      IF(J.EQ.2)            M2=M3+M3-M4                                 INTR2180
      GO TO 45                                                          INTR2190
   42 M4=M3+M3-M2                                                       INTR2200
      GO TO 45                                                          INTR2210
   43 M2=M3                                                             INTR2220
      M4=M3                                                             INTR2230
   45 IF(J.LE.3)            GO TO 46                                    INTR2240
      A1=X2-X(J-3)                                                      INTR2250
      M1=(Y2-Y(J-3))/A1                                                 INTR2260
      GO TO 47                                                          INTR2270
   46 M1=M2+M2-M3                                                       INTR2280
   47 IF(J.GE.LM1)          GO TO 48                                    INTR2290
      A5=X(J+2)-X5                                                      INTR2300
      M5=(Y(J+2)-Y5)/A5                                                 INTR2310
      GO TO 50                                                          INTR2320
   48 M5=M4+M4-M3                                                       INTR2330
C NUMERICAL DIFFERENTIATION                                             INTR2340
   50 IF(I.EQ.LP1)          GO TO 52                                    INTR2350
      W2=ABS(M4-M3)                                                     INTR2360
      W3=ABS(M2-M1)                                                     INTR2370
      SW=W2+W3                                                          INTR2380
      IF(SW.NE.0.0)         GO TO 51                                    INTR2390
      W2=0.5                                                            INTR2400
      W3=0.5                                                            INTR2410
      SW=1.0                                                            INTR2420
   51 T3=(W2*M2+W3*M3)/SW                                               INTR2430
      IF(I.EQ.1)            GO TO 54                                    INTR2440
   52 W3=ABS(M5-M4)                                                     INTR2450
      W4=ABS(M3-M2)                                                     INTR2460
      SW=W3+W4                                                          INTR2470
      IF(SW.NE.0.0)         GO TO 53                                    INTR2480
      W3=0.5                                                            INTR2490
```

```
      W4=0.5                                                            INTR2500
      SW=1.0                                                            INTR2510
   53 T4=(W3*M3+W4*M4)/SW                                               INTR2520
      IF(I.NE.LP1)        GO TO 60                                      INTR2530
      T3=T4                                                             INTR2540
      SA=A2+A3                                                          INTR2550
      T4=0.5*(M4+M5-A2*(A2-A3)*(M2-M3)/(SA*SA))                         INTR2560
      X3=X4                                                             INTR2570
      Y3=Y4                                                             INTR2580
      A3=A2                                                             INTR2590
      M3=M4                                                             INTR2600
      GO TO 60                                                          INTR2610
   54 T4=T3                                                             INTR2620
      SA=A3+A4                                                          INTR2630
      T3=0.5*(M1+M2-A4*(A3-A4)*(M3-M4)/(SA*SA))                         INTR2640
      X3=X3-A4                                                          INTR2650
      Y3=Y3-M2*A4                                                       INTR2660
      A3=A4                                                             INTR2670
      M3=M2                                                             INTR2680
C DETERMINATION OF THE CCEFFICIENTS                                     INTR2690
   60 Q2=(2.0*(M3-T3)+M3-T4)/A3                                         INTR2700
      Q3=(-M3-M3+T3+T4)/(A3*A3)                                         INTR2710
C COMPUTATION OF THE PCLYNCMIAL                                         INTR2720
   70 DX=UK-P0                                                          INTR2730
   80 V(K)=Q0+DX*(Q1+DX*(Q2+DX*Q3))                                     INTR2740
      RETURN                                                            INTR2750
C ERROR EXIT                                                            INTR2760
   90 WRITE (6,2090)                                                    INTR2770
      GC TO 99                                                          INTR2780
   91 WRITE (6,2091)                                                    INTR2790
      GC TO 99                                                          INTR2800
   95 WRITE (6,2095)                                                    INTR2810
      GC TO 97                                                          INTR2820
   96 WRITE (6,2096)                                                    INTR283C
   97 WRITE (6,2097)    I,X(I)                                          INTR2840
   99 WRITE (6,2099)    LO,NO                                           INTR2850
      RETURN                                                            INTR2860
C FCRMAT STATEMENTS                                                     INTR2870
 2090 FCRMAT(1X/22H  ***   L = 1 OR LESS./)                             INTR2880
 2091 FORMAT(1X/22H  ***   N = 0 OR LESS./)                             INTR2890
 2095 FCRMAT(1X/27H  ***   IDENTICAL X VALUES./)                        INTR2900
 2096 FCRMAT(1X/33H  ***   X VALUES CUT CF SEQUENCE./)                  INTR2910
 2097 FCRMAT(6H    I =,I7,10X,6HX(I) =,E12.3)                           INTR2920
 2099 FCRMAT(6H    L =,I7,10X,3HN =,I7/                                 INTR2930
     1       36H ERROR DETECTED IN ROLTINE     INTFPL)                  INTR2940
      END                                                               INTR2950
```

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